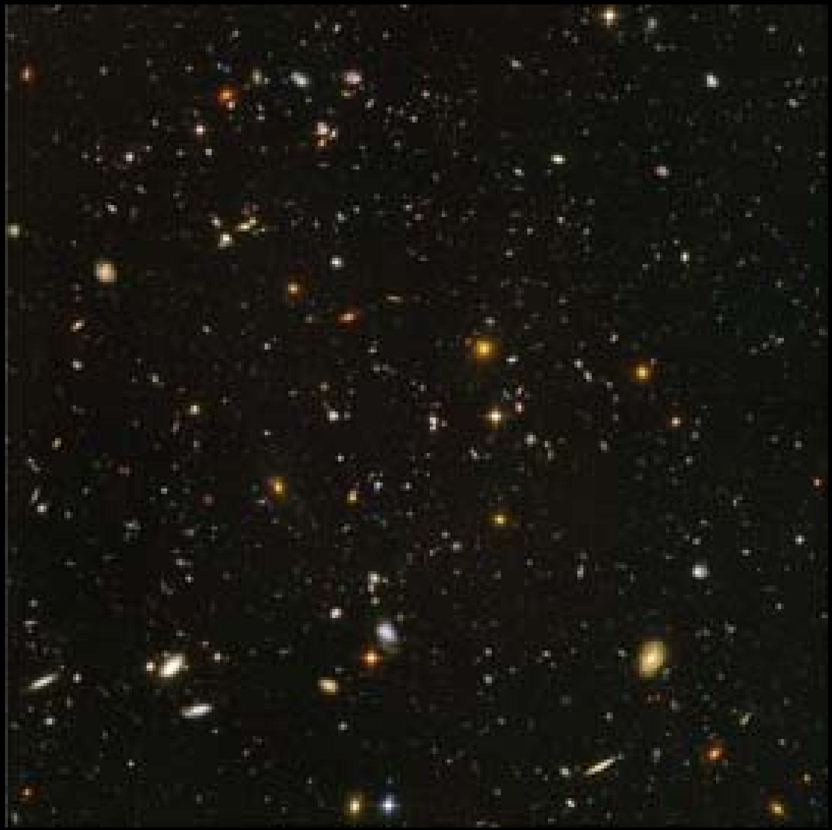
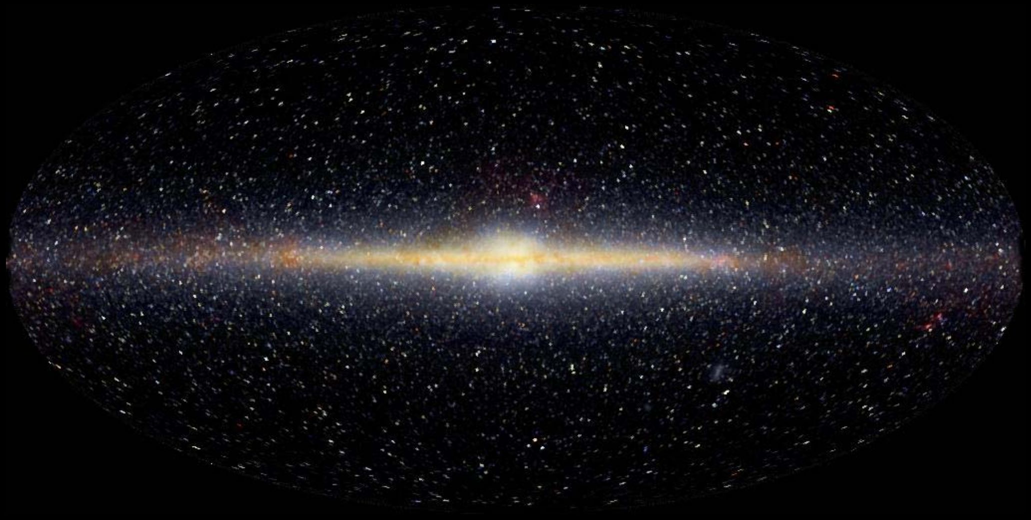


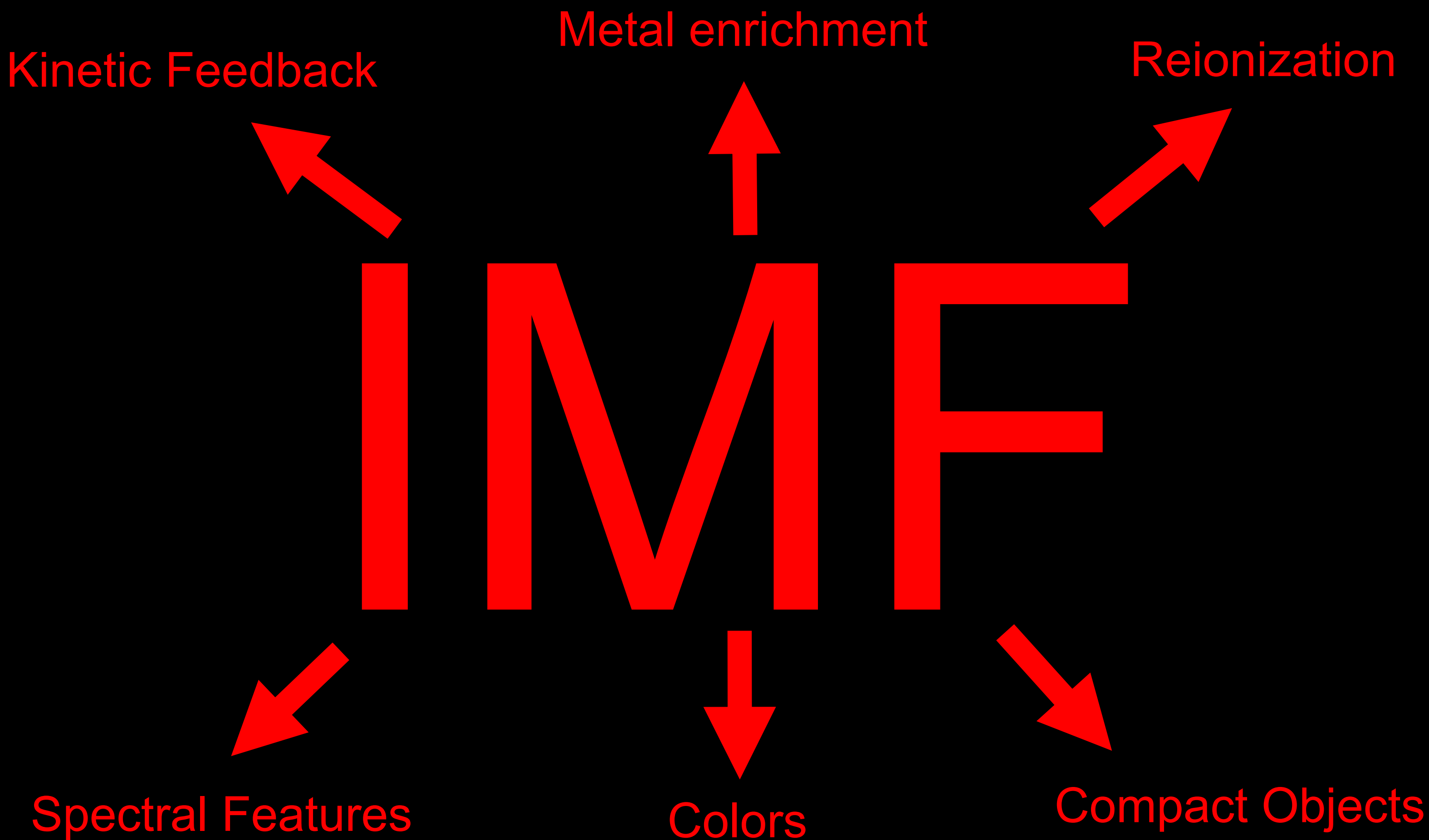
CEMP Stars and the IMF During the "Dark Ages"

Jason Tumlinson

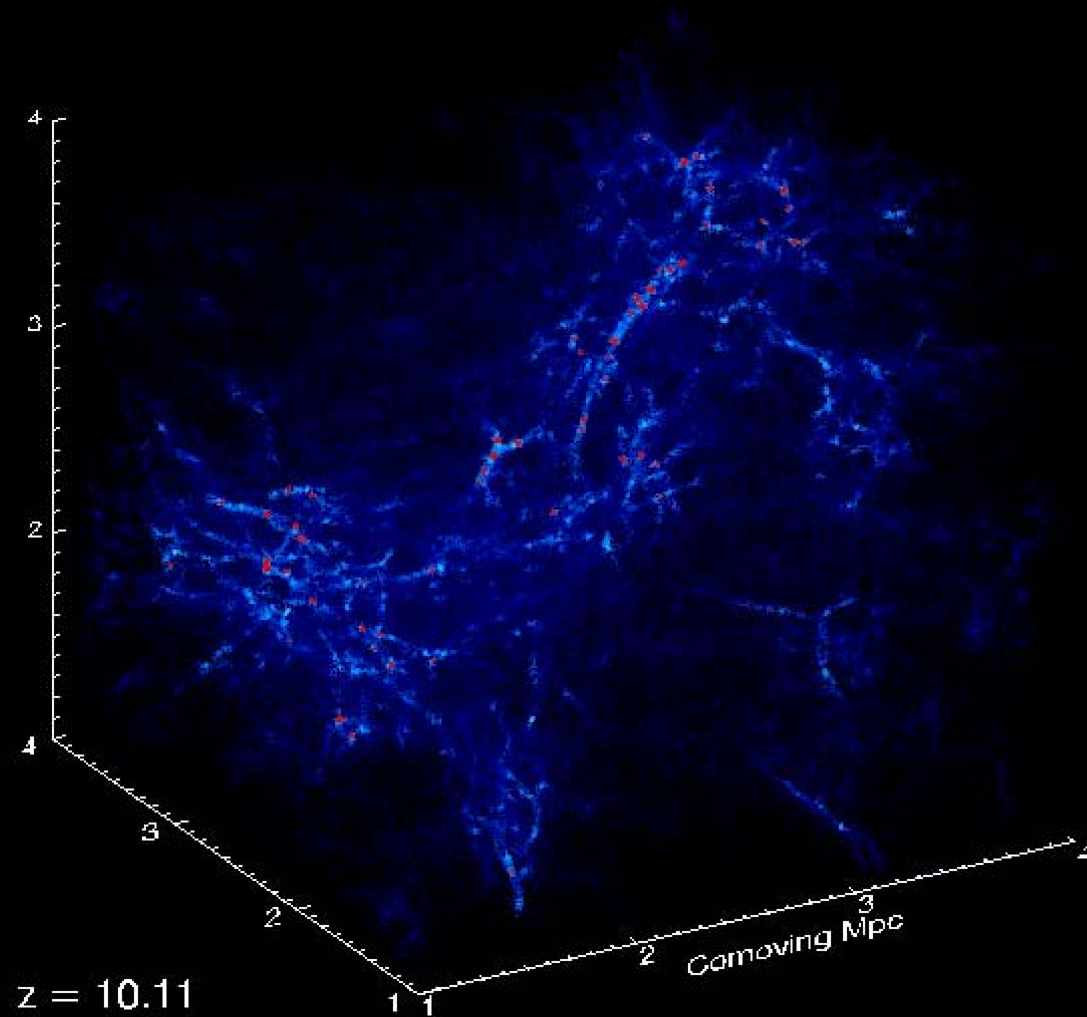
Yale University & KITP



October 10, 2007


Metal enrichment
Kinetic Feedback
Reionization
IMF
Spectral Features
Colors
Compact Objects

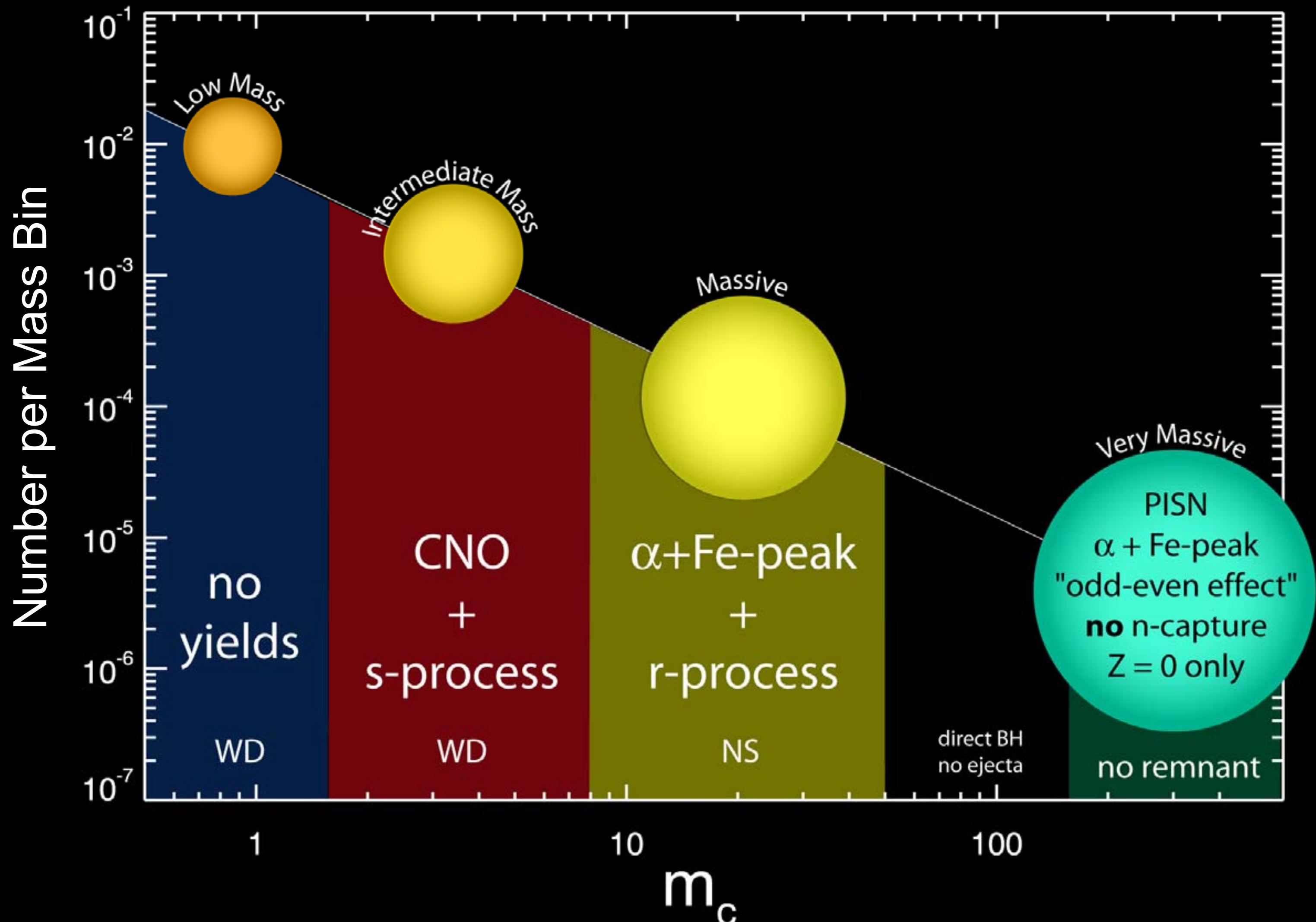
The Milky Way During the Dark Ages



At z = 10, the MW consisted of a few dozen halos of $M > 10^8\ M_\odot$.

These pieces will be quite faint at high *z* and direct IMF constraints will be challenging.

Fortunately, the Milky Way contains representatives from this early epoch, in the form of long-lived low-mass stars that retain a memory of early chemical evolution, and the IMF.

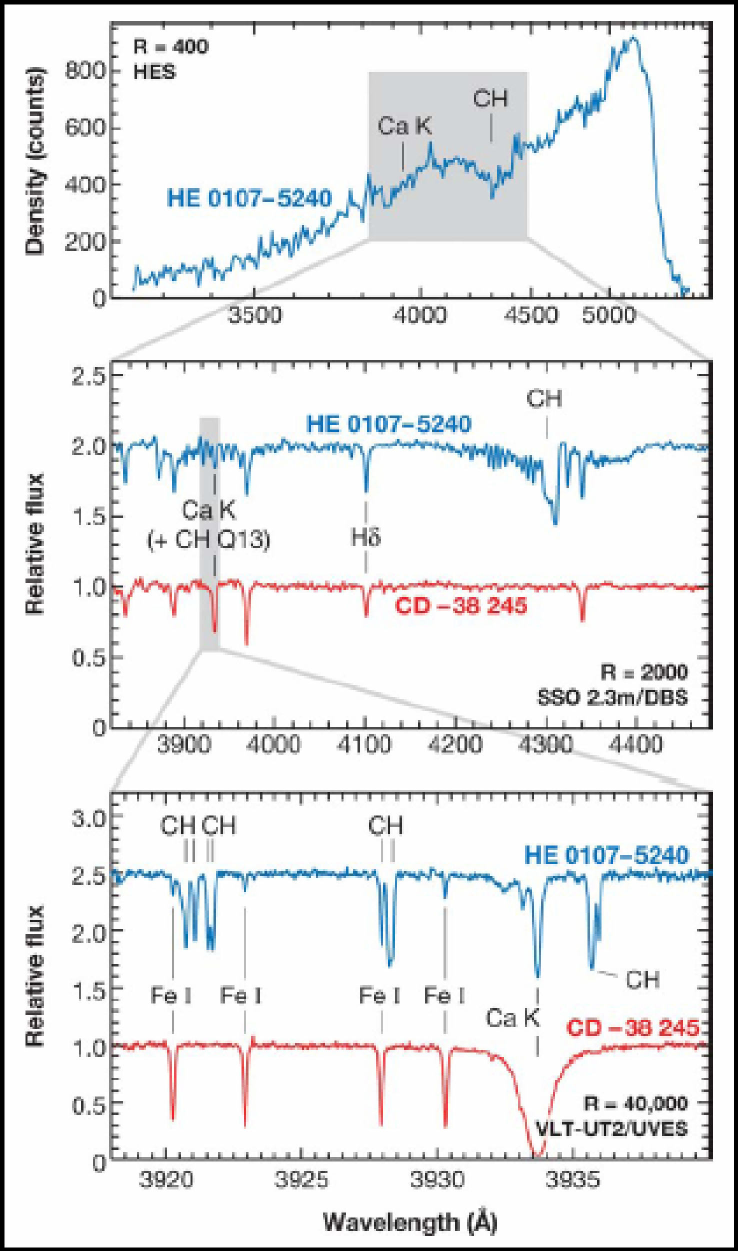


Key Idea: The chemical signatures of stars vary with initial mass and metallicity in complex but calculable fashion.

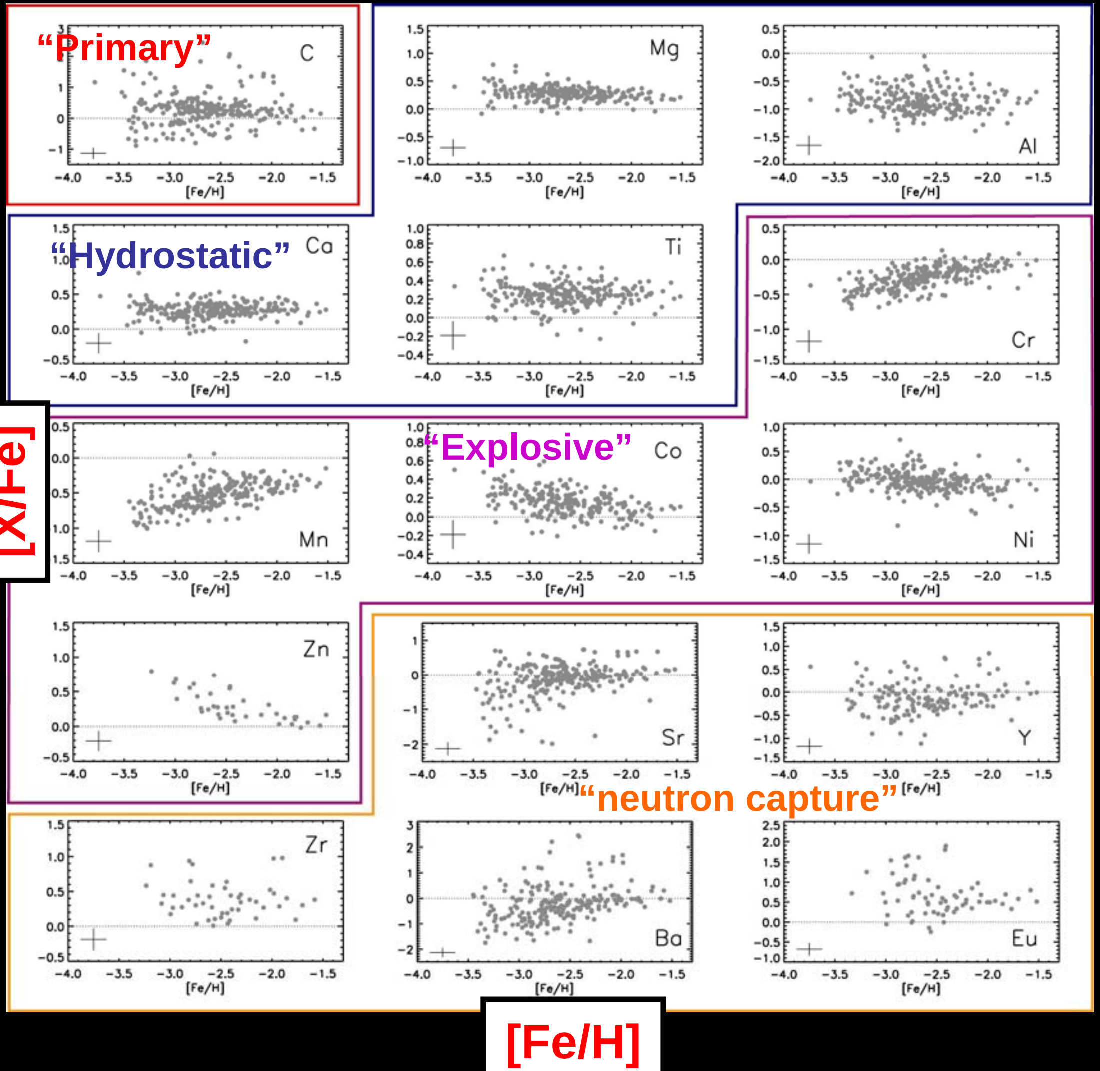
Our strategy is to use <u>robust</u> and <u>distinct</u> signatures of stellar mass to diagnose IMF.

A New Era in Chemical Abundance Surveys

Beers & Christlieb (2005) ARA&A

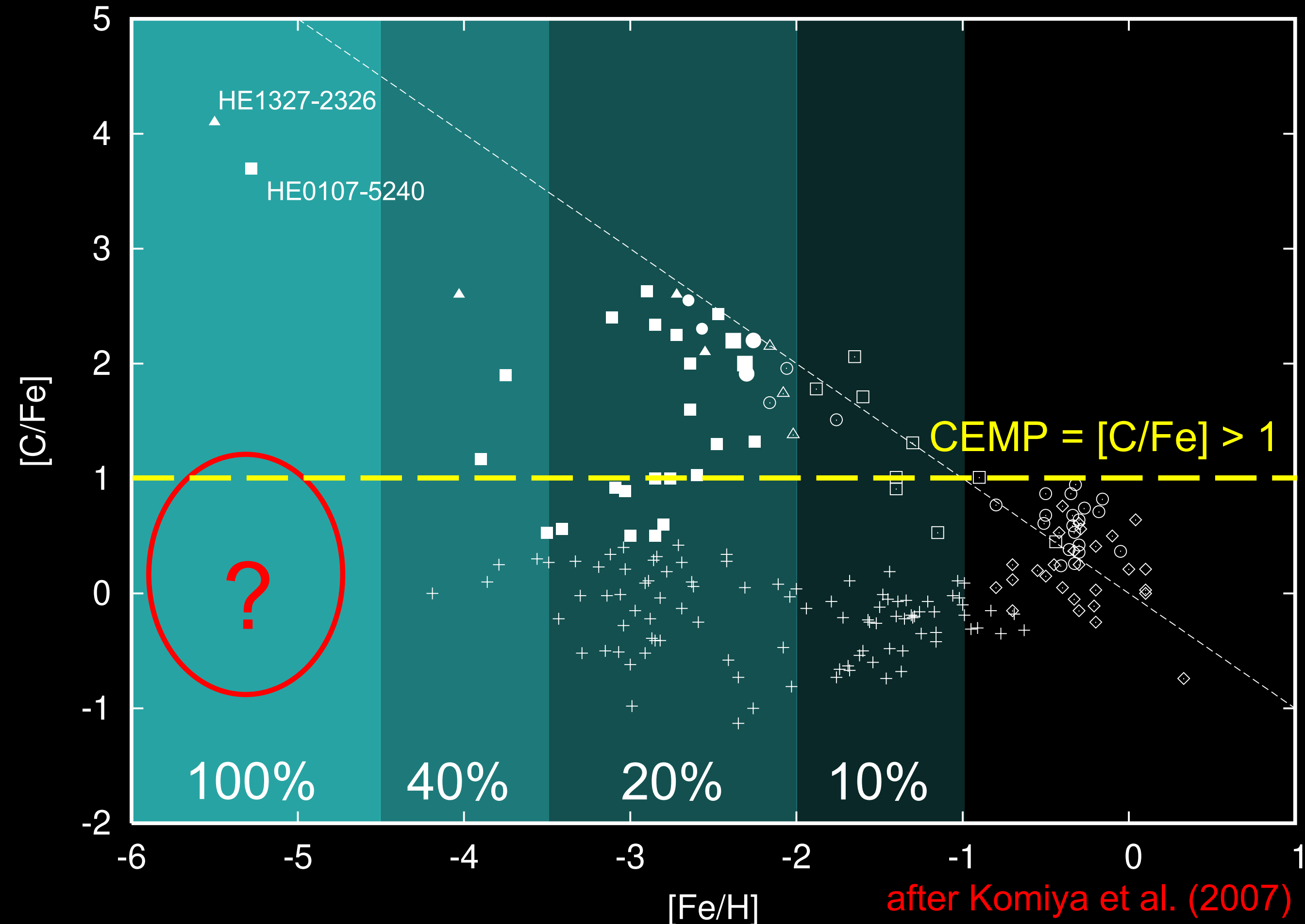


HERES Survey - Barklem et al. (2005) – 15 elements in 253 stars



Ongoing or upcoming surveys:
SDSS/SEGUE+APOGEE, DART, RAVE, LAMOST, WFMOS (?), GAIA

Carbon-Enhanced Metal-Poor Stars (CEMPs):



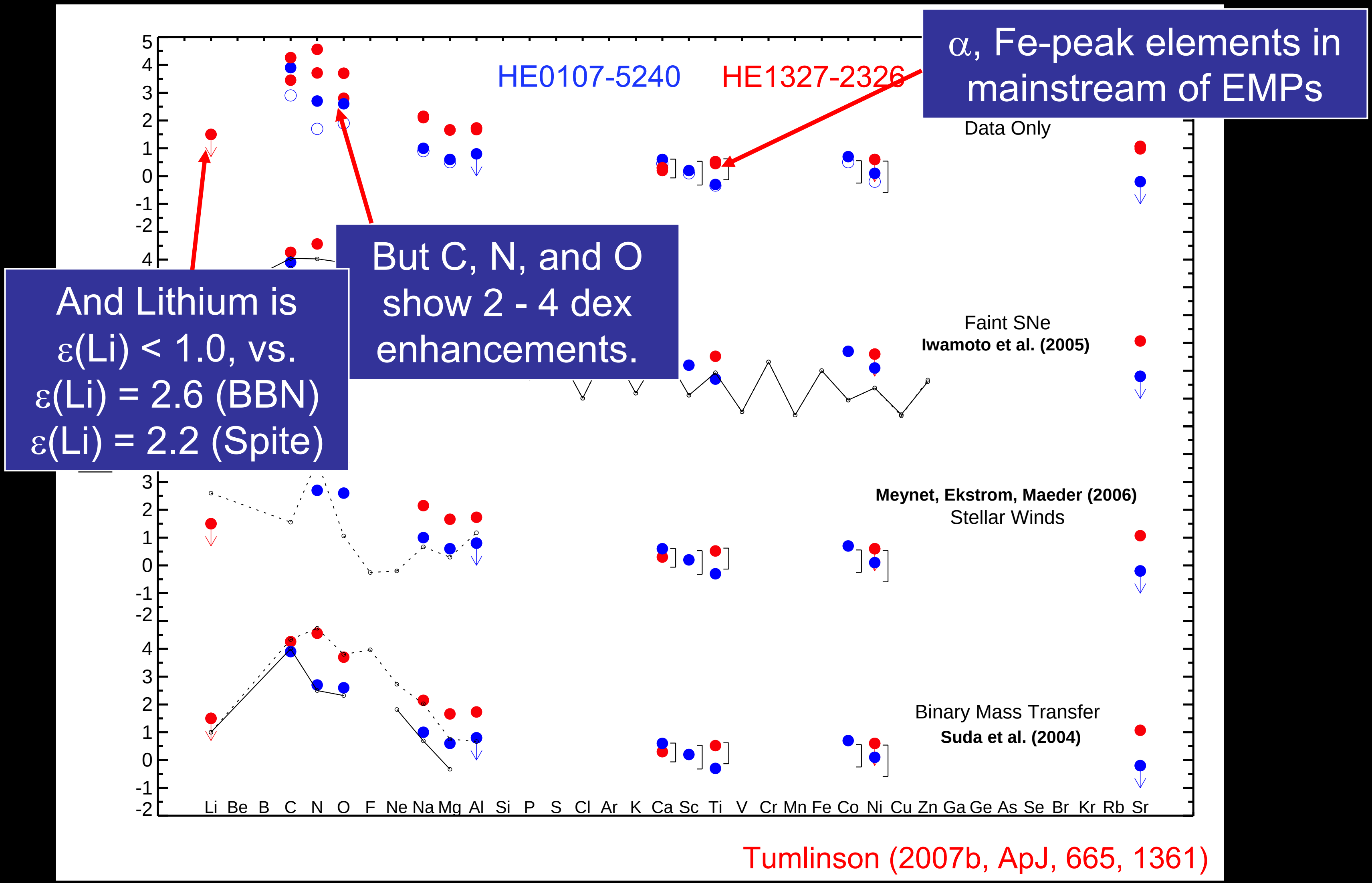
after Komiya et al. (2007)

The Answer: CEMP stars are born as low-mass partner in a binary system.

80% are s-process rich from AGB ("CEMP-s"; Aoki et al. 2007)

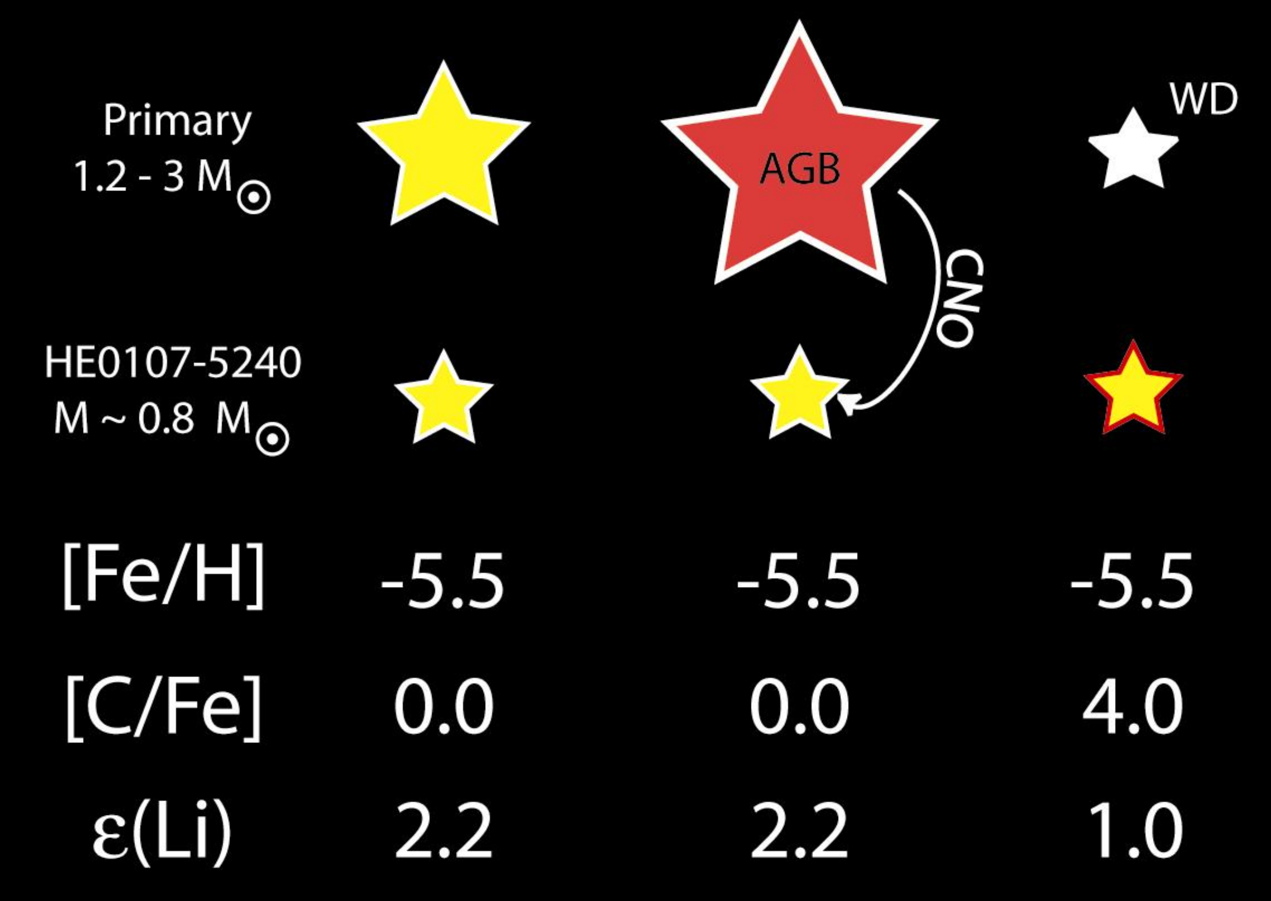
CEMP-s consistent with 100% binarity (Lucatello et al. 2005).

What about the HMPs?



To match ε(Li) < 1.0, "dilution mass" must be small: M ~ 0.01 - 0.1 $M_{\odot}$.

This rules out "Faint SNe" and "Stellar Winds" models, which require dilution of massive star ejecta into $10^4 – 10^5$ $M_{\odot}$.



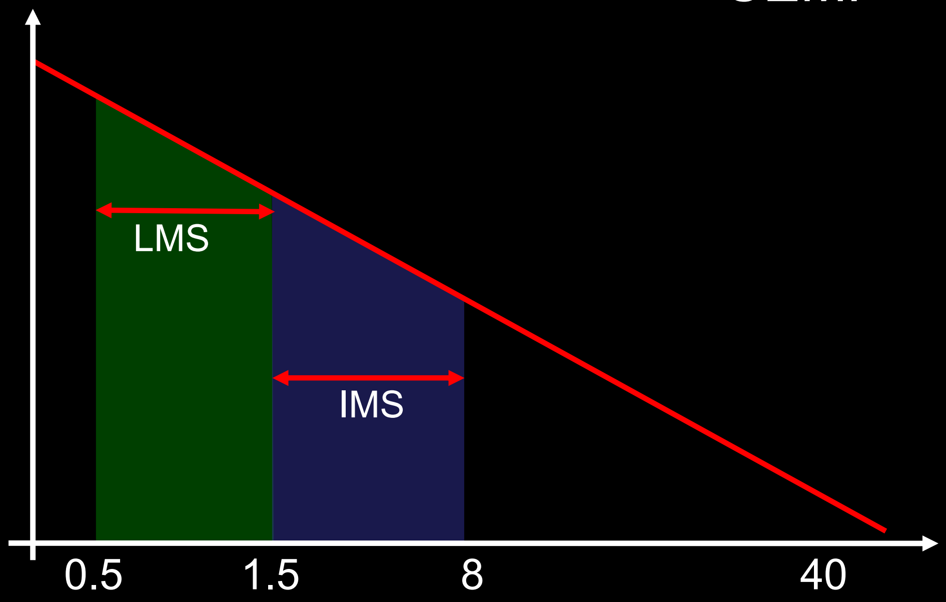
The ratio of C-rich to C-normal stars in a population measures the ratio of intermediate to low-mass stars in the IMF!

Estimate from early CEMP studies: $M_C > 0.8\ M_\odot$ (Lucatello et al.2005).

There are no C-normal stars at [Fe/H] = -5.5, so $M_c = 1.5 - 6\ M_\odot$ (Tumlinson07b).

Komiya et al. (2007) find $m_c \sim 10\ M_\odot$ to match s-element patterns of CEMPs.

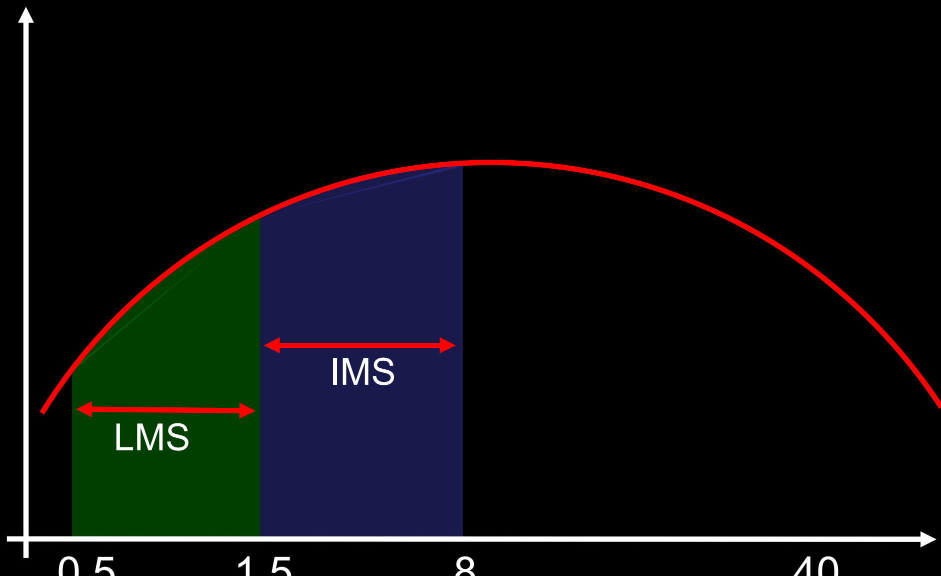
From f_{CEMP} to the IMF

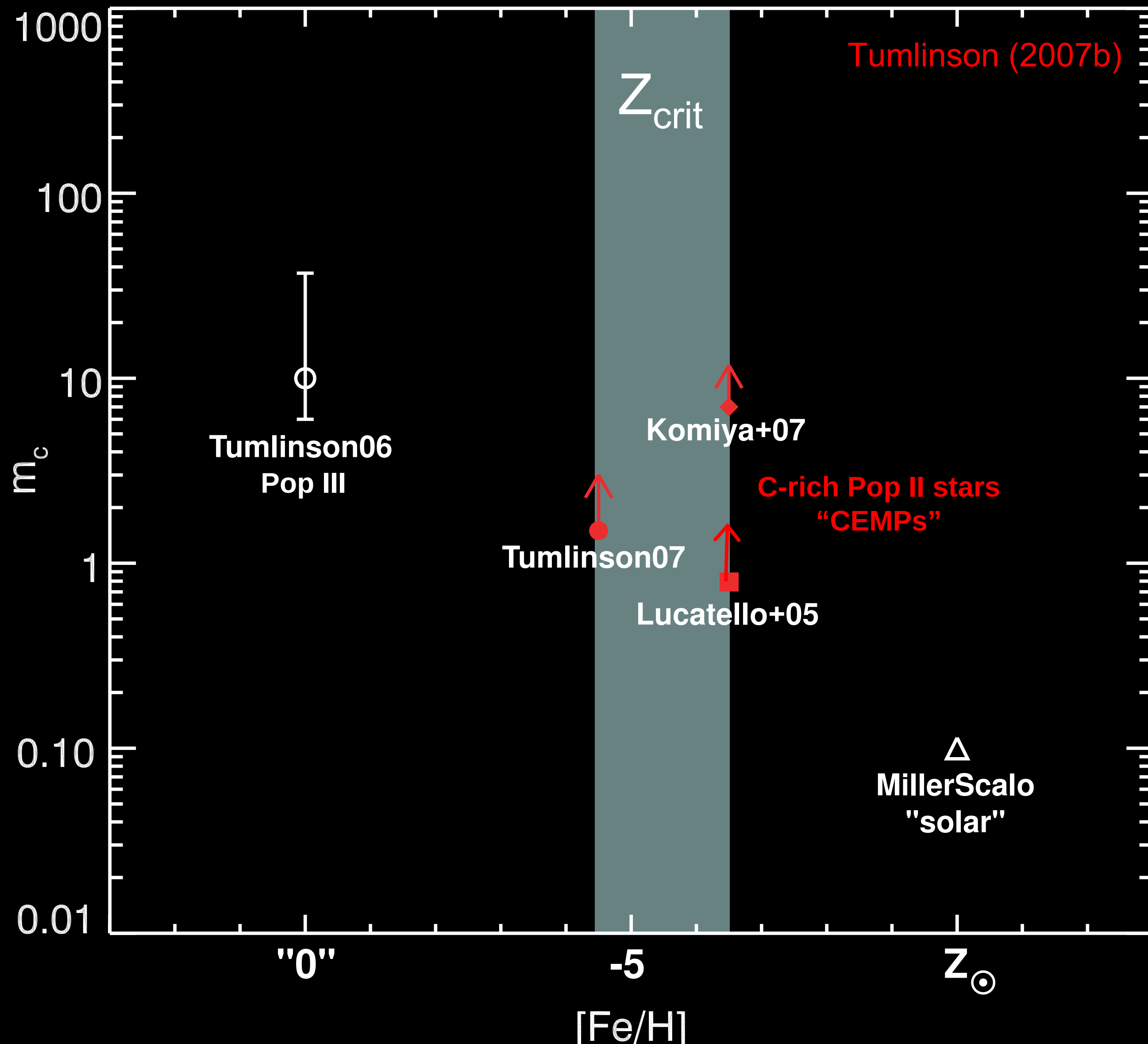


CEMP = Binary of

M_2 = 0.5 – 0.8 $M_\odot$ and M_1 = 1.5 – 8 $M_\odot$.

f_{CEMP} increases in a skewed IMF when the number of low-mass star formed in binaries with an IMS increases relative to the number formed in isolation.





Why would the IMF favor intermediate mass, if $Z \sim 10^{-3} Z_\odot$ is high enough to cool efficiently (Bromm+Loeb03, Schneider+02)?

The CMB and the Characteristic Stellar Mass

Studies of local star formation (Larson ‘98,’05; Jappsen et al. ’05) suggest that the characteristic mass of stars responds to the minimum *T* at which gas becomes optically thick to cooling radiation and thermally coupled to dust.

$$M_J \approx M_\odot \left(\frac{n}{10^3\,cm^{-3}}\right)^{-1/2} \left(\frac{T}{10K}\right)^{3/2}$$

At low redshift, $T = T_{min} = 8$ K is set by metal and dust cooling.

But at high *z*, the CMB itself is the minimum gas/dust temperature!

$$m_C \approx 0.7\ M_\odot\ [T_{CMB}/10K]^{1.70\text{-}3.35}$$

$z = 5, 10, 20 \longrightarrow T_{CMB} = 16, 30, 57\ K \longrightarrow M_C = 1.6, 5, 14\ M_\odot$

Thus stars formed early in MW history, at z > 5, should be affected!

Note: this “theory” posits that only thermal conditions influence m_C.

Two Predictions of the CMB-IMF Hypothesis

(Tumlinson 2007a, ApJL, 664, 63)

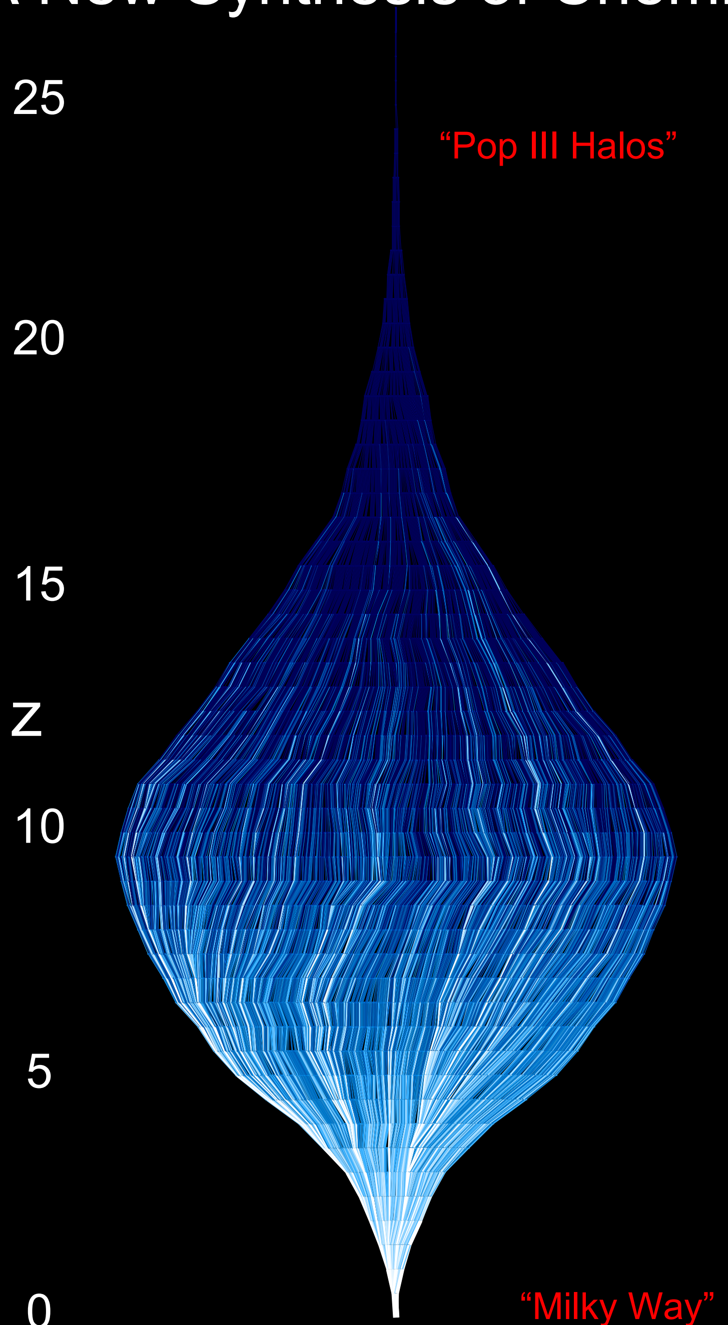
(1)

Stochastic, local phenomenon of chemical evolution implies that, on average, more metal-poor stars form earlier, so f_{CEMP} should increase with declining [Fe/H].

(2)

Inside-out construction the halo causes extended epoch of star formation at fixed [Fe/H], so f_{CEMP} should increase in "older" regions of the Galaxy and decrease in "younger" regions, at fixed metallicity.

A New Synthesis of Chemical Evolution & Structure Formation



<u>HIERARCHICAL</u>: Presently based on semi-analytic halo merger trees, to allow for chemical evolution calculations much faster than full hydro simulations, much more realistic than "classical" GCE.

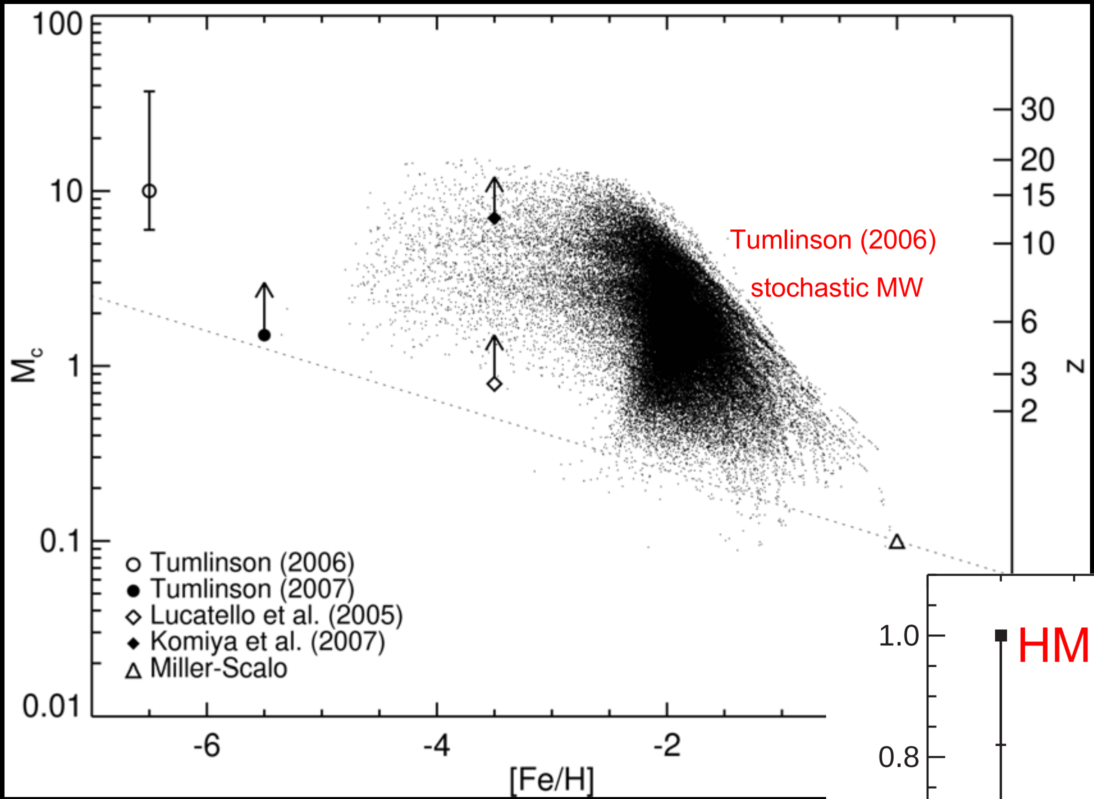
<u>STOCHASTIC</u>: Within each node, gas budget is tracked and new star formation samples the IMF **"one-star-at-a-time"**. New star formation is assigned a metallicity based on random sampling of "enrichment zones" from prior generations.

<u>UNIFIED</u>: Best of all, these "nodes" can be modeled as individual galaxies for direct comparisons to data at high redshift – this is also the core of a galaxy formation code.

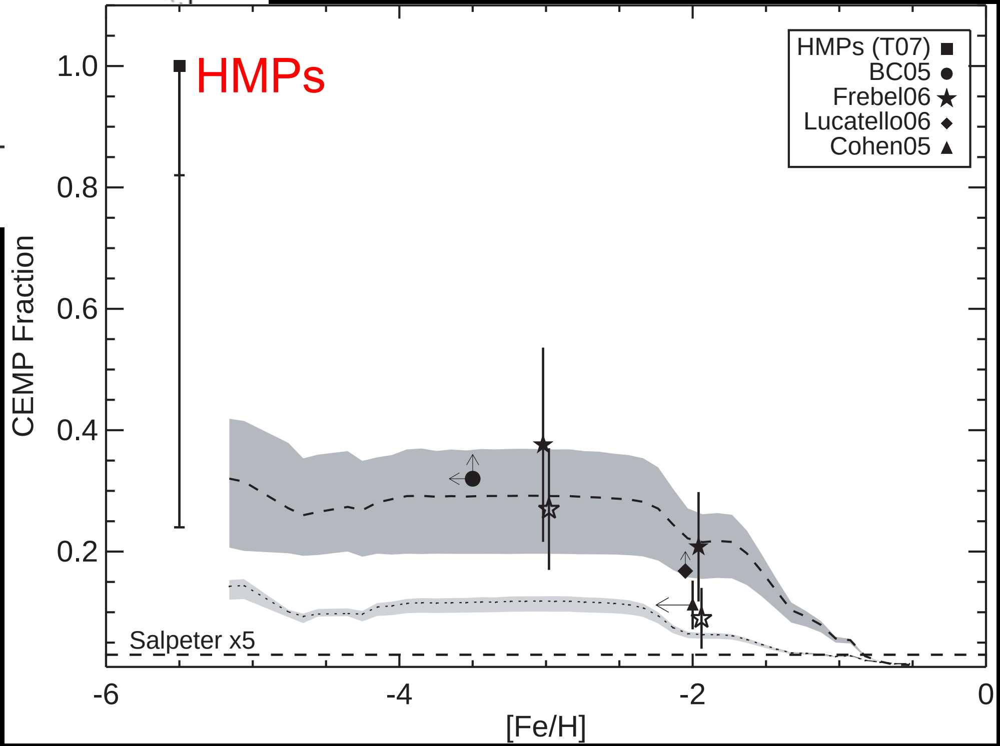
Tumlinson 2006, ApJ 641, 1

Prediction 1: Variation of CEMP Fraction with Metallicity

(Tumlinson 2007a, ApJL, 664, L63)

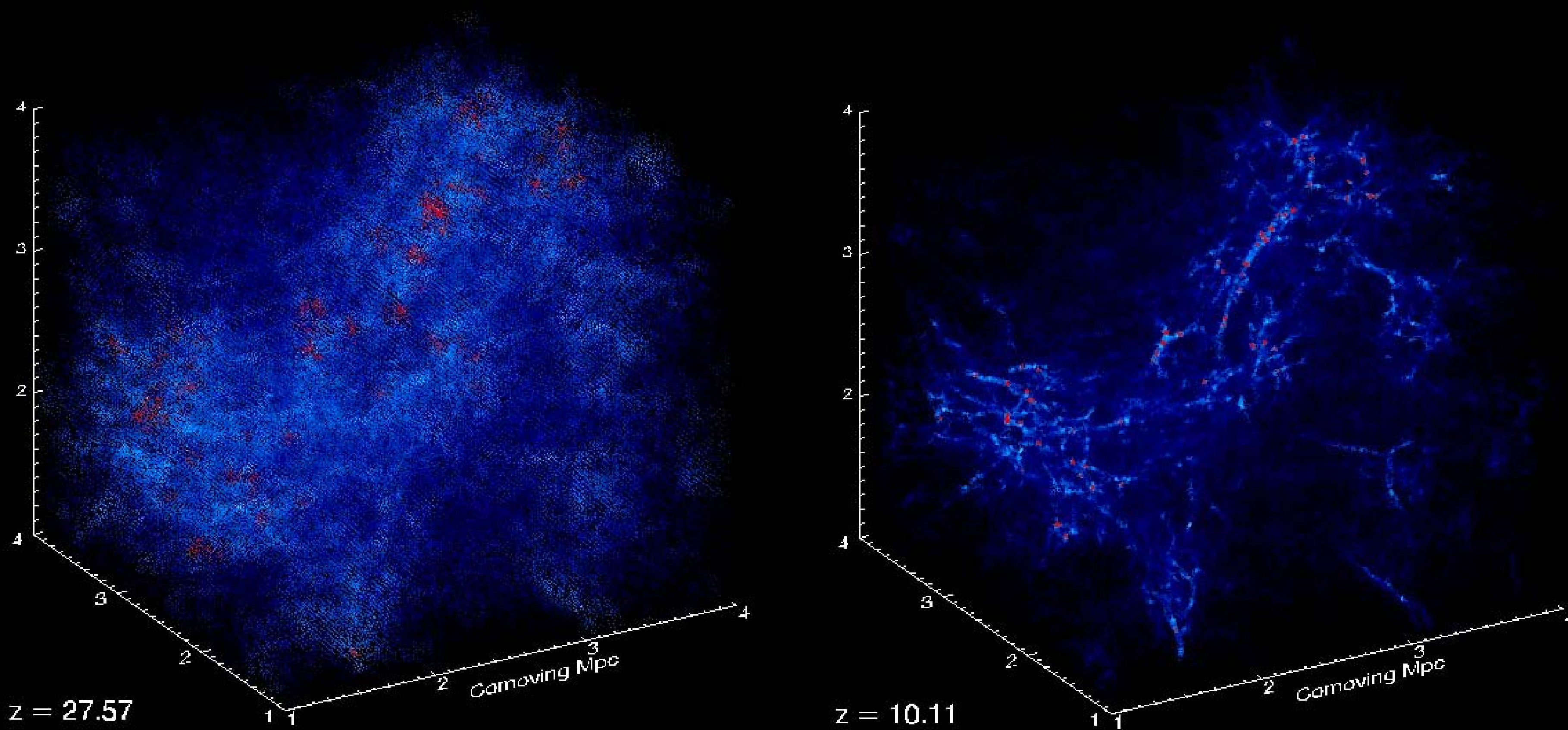


Chemical evolution proceeds stochastically, such that more metal-poor stars tend to form earlier.



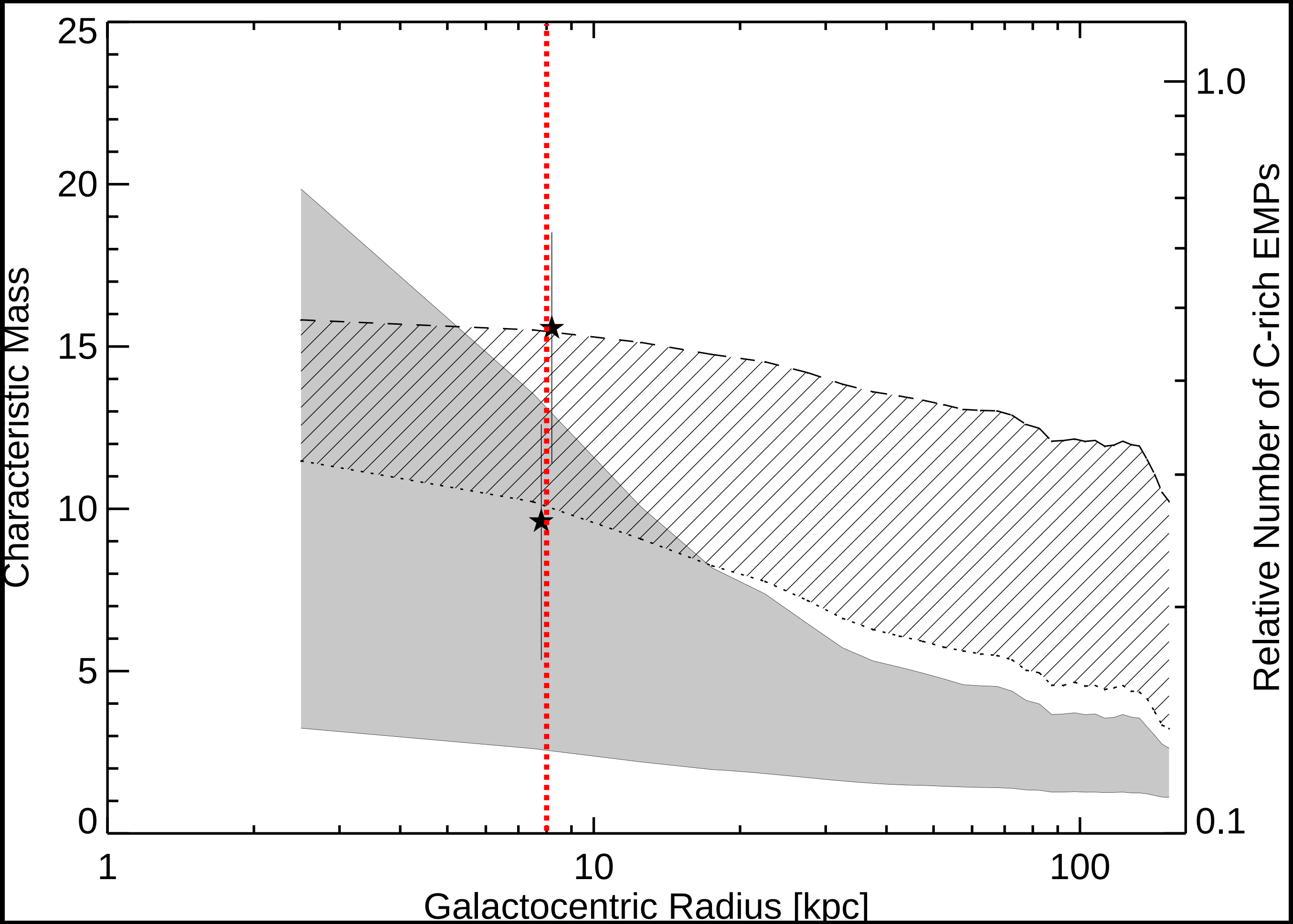
With a CMB-IMF, f_{CEMP} is high at low [Fe/H], and declines with increasing [Fe/H] as the typical formation redshift at a given metallicity declines.

Key Idea for Prediction 2: The Halo is Built from the Inside Out. . .



. . . With the oldest pieces centrally concentrated.

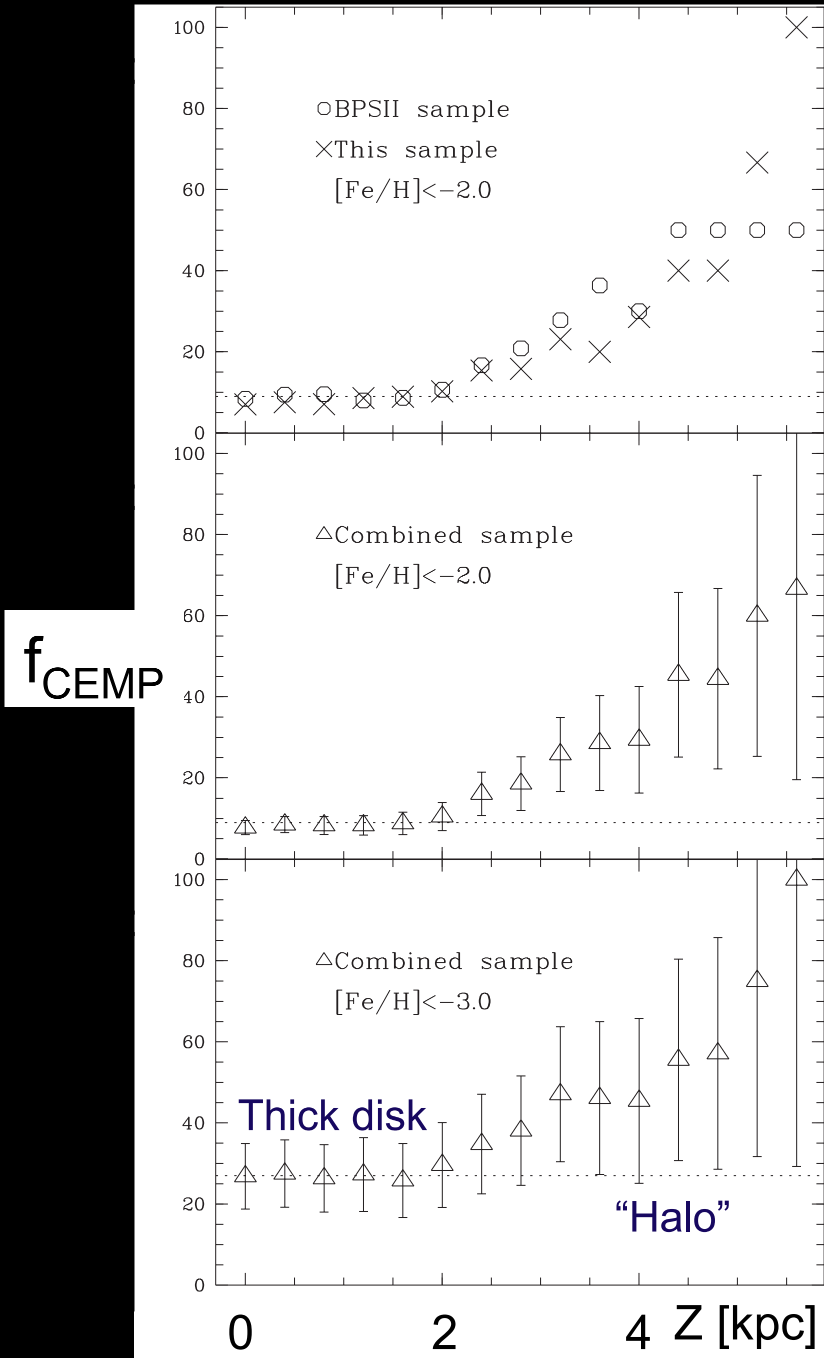
Prediction 2: Variation of CEMPs with Galactic Location



$$\frac{N_{CEMP}}{N_{CEMP}+N_{C\text{-normal}}}$$

The CMB-dominated mass scale at ~ 10 kpc is 2 -10 $M_{\odot}$.

At a given metallicity, stars in the inner halo are older, and this gradient gives a gradient of C-rich/C-normal fraction.



Prediction 2 already seen?

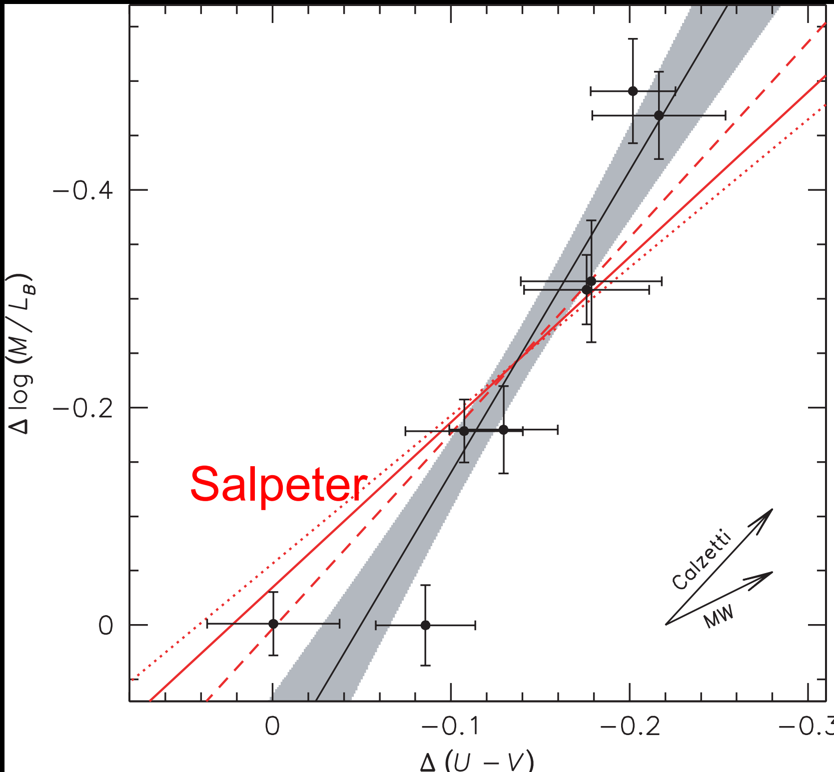
- 174 bright Hamburg-ESO stars, (Frebel et al. 2006) find change in f_{CEMP} with [Fe/H] and with scale height above the Galactic plane.
- Higher incidence of CEMPs in the stellar halo, <z> ~ 7, than in the thick disk, <z> ~ 2 – 3.
- Indicates more than just a metallicity dependence, which is explained by the CMB-IMF hypothesis.
- Will be tested by upcoming SEGUE results with much better statistics.

Surveys for Next Generation Galactic Archaeology

~10^9 GAIA (ESA)

> 10^6 WFMOS(?)

Same effect seen in old massive galaxies?



van Dokkum (2008) astro-ph/0710.0875

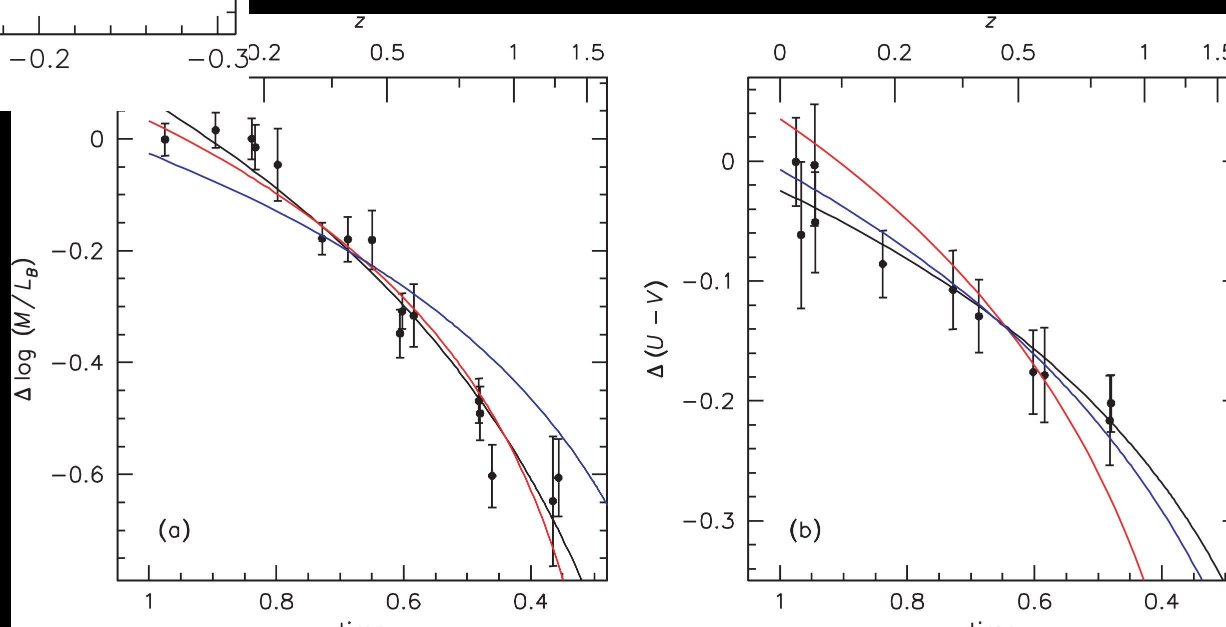
technique from Tinsley (1980)

A sample of “red and dead” massive cluster galaxies show faster evolution in M/L than expected for “standard” IMFs, and are consistent with IMFs flatter than Salpeter in the region of ~1-2 $M_\odot$.

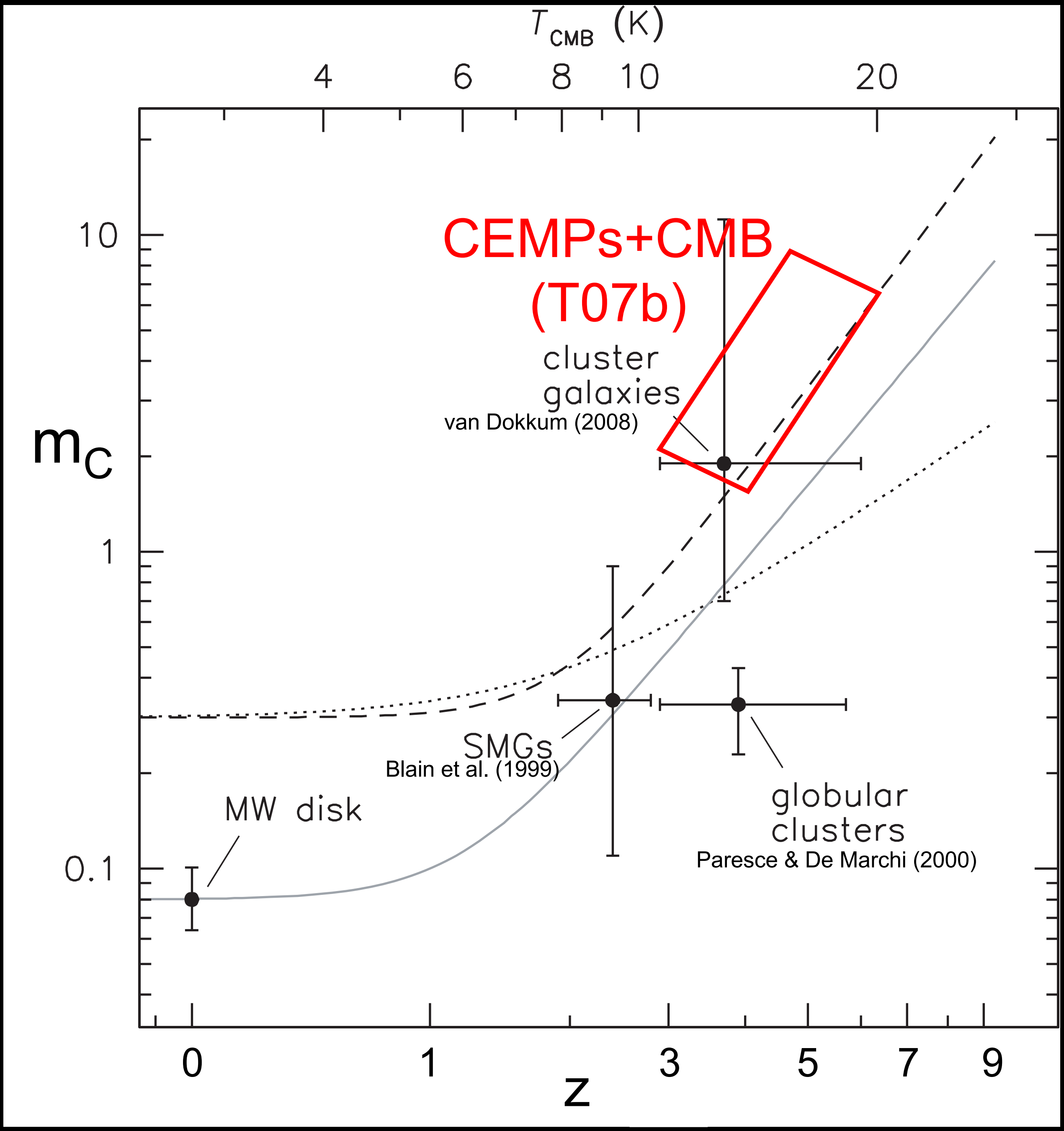
Salpeter + z_{form} = 2

Salpeter + z_{form} = 6

“Flat IMF” + z_{form} = 6



Concordance of IMF indicators



Conclusions and Arguments

- Along with previous constraints on Pop III stars (Tumlinson 2006), there is good evidence for evolution in the IMF toward higher mass at high redshift.
- IMF constraints on early stellar populations obtained from stellar abundance studies should be taken as constraints on fundamental star formation theory.
- Information can be obtained on mass function (both peak mass and power law slope) and on multiplicity.
- This is a growth area as the number of halo stars with good abundances will increase by many orders of magnitude by 2012.

Questions for Discussion Time:

4What determines the transition at very early times from high mass stars >100M_sun to order M_sun . Metals Z~ 10^(-5) transition. Why?

A: Above $Z_{cr} \sim 10^{-5}$ to 10^{-3}, this transition is mediated by the CMB; IMF can be top-heavy even at $Z = Z_{\odot}$.

- How do thermal conditions (Larson) interact with turbulence (Padoan/Nordlund) in setting m_c and the power-law slope?
- Are the conditions for binarity right at extreme low Z?
- How do globular clusters fit into this picture, when the oldest appear to form at $z > 4$ with $m_c \sim 0.3$. Because they are not in bound halos?
- When is it more sensible to invoke a varying IMF instead of individual *ad hoc* reasons for each observation (dust, bad isochrones, ignorance of AGB phenomenon)?
- The IMF is "normal" even in nearby regions where naïve treatments of the thermal physics predict top-heavy (i.e. Arches cluster). Why, and what are we missing? Are conditions in the early Universe different?