Galaxy Formation and Chemical Evolution

A New Synthesis Reveals the First Stars

Mass, Light, and Chemistry Workshop

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Still Unsolved Problems

- Main goal: What is the IMF in primordial gas?

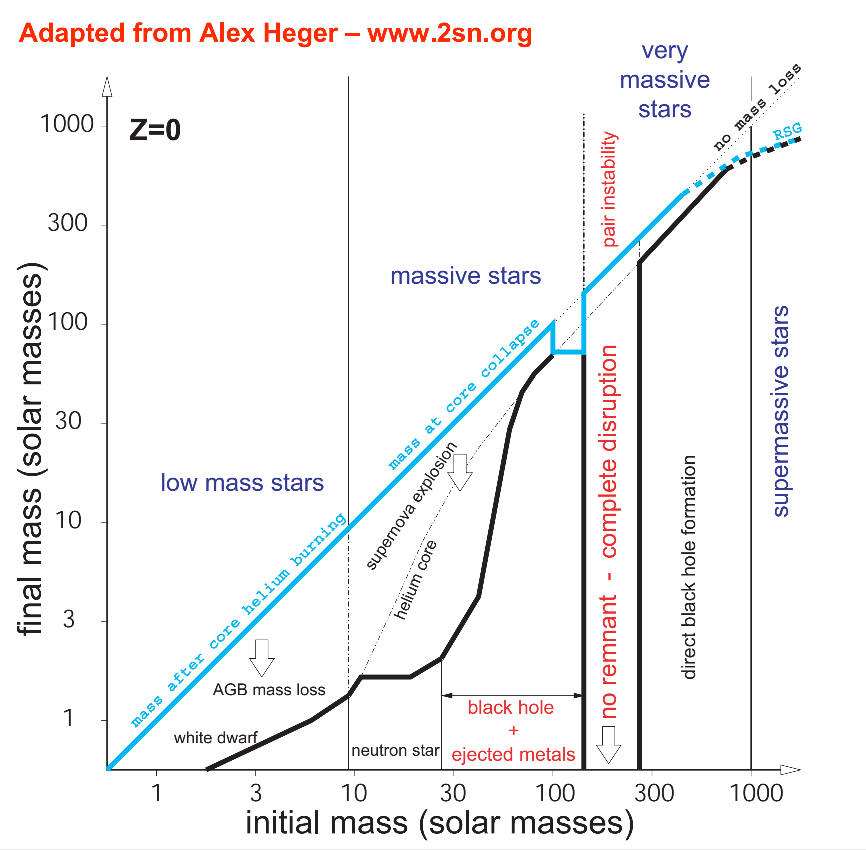
  Secondary goals: When do metal-free stars end? or, What is Z_{crit}?

  What are their contributions to reionization?

- Silk: "Theory cannot (yet) say anything definitive" about balance between accretion/feedback and therefore specify mass function.
- Therefore an independent, empirical approach to the IMF is desirable.

I will approach these problems with a new synthesis of galaxy formation and detailed chemical evolution models that address the large and growing database of Galactic halo stellar abundances.

The “VMS Hypothesis”


Adapted from Alex Heger – www.2sn.org

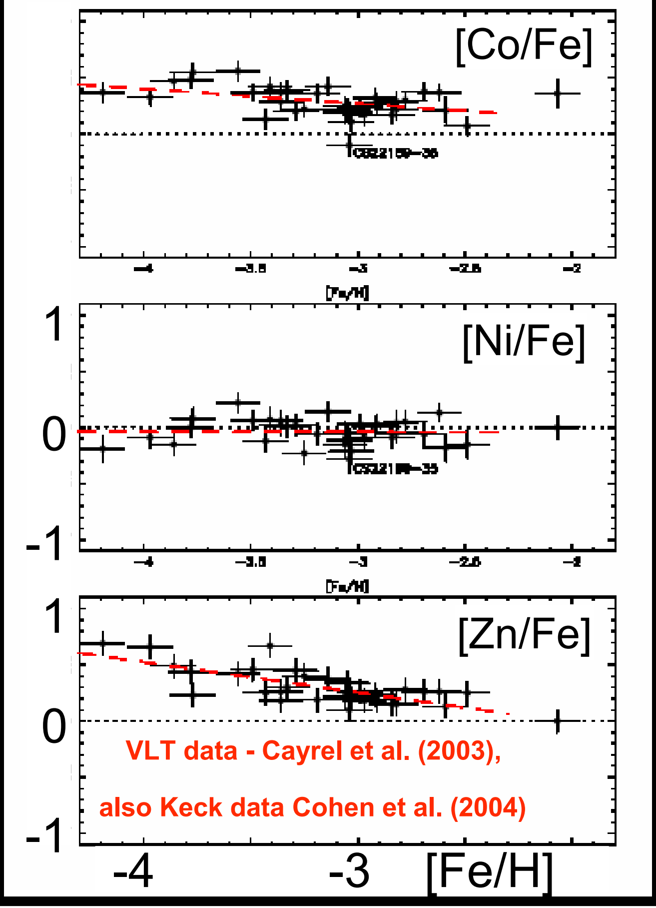
<ins>From Tumlinson, Venkatesan, & Shull (2004):</ins>

The Strong VMS Hypothesis: No stars below M = 140 $M_{\odot}$ form (only VMS do) or in terms of metal production, no Type II SN or HN arise from the first stars.

The Weak VMS Hypothesis: Stars with 8 – 50 $M_{\odot}$,the progenitors of Type II SN, form *in addition* to VMS (but VMS probably produce most of the Fe).

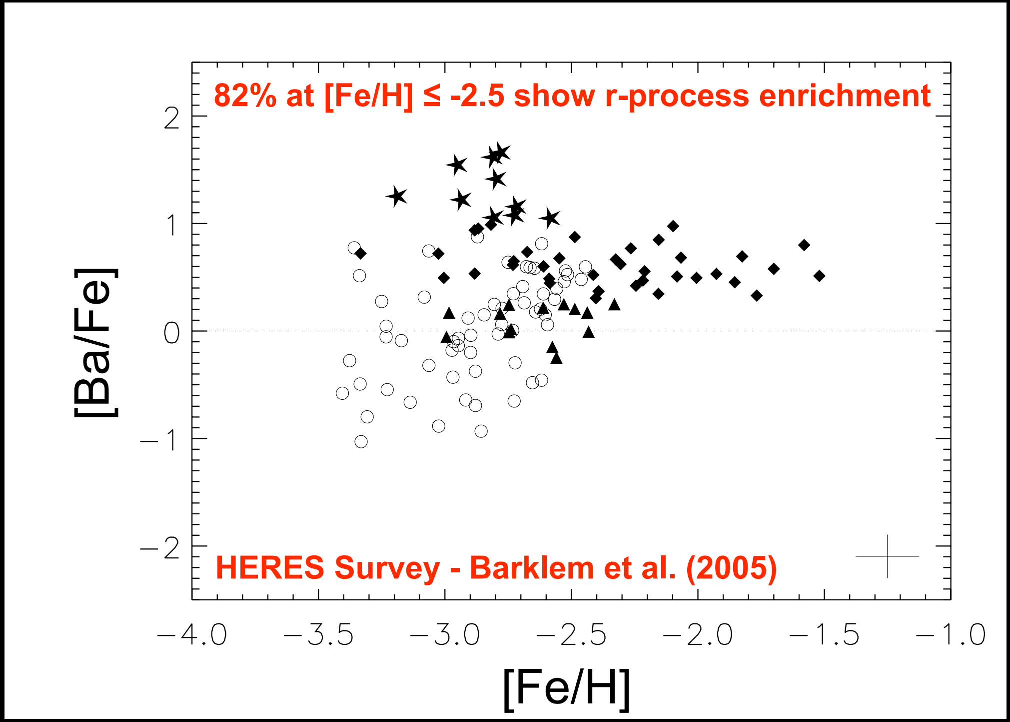
This distinction allows IMF to make detailed predictions for nucleosynthesis.

The First Stars via Galactic Chemical Evolution



VLT data - Cayrel et al. (2003),

also Keck data Cohen et al. (2004)



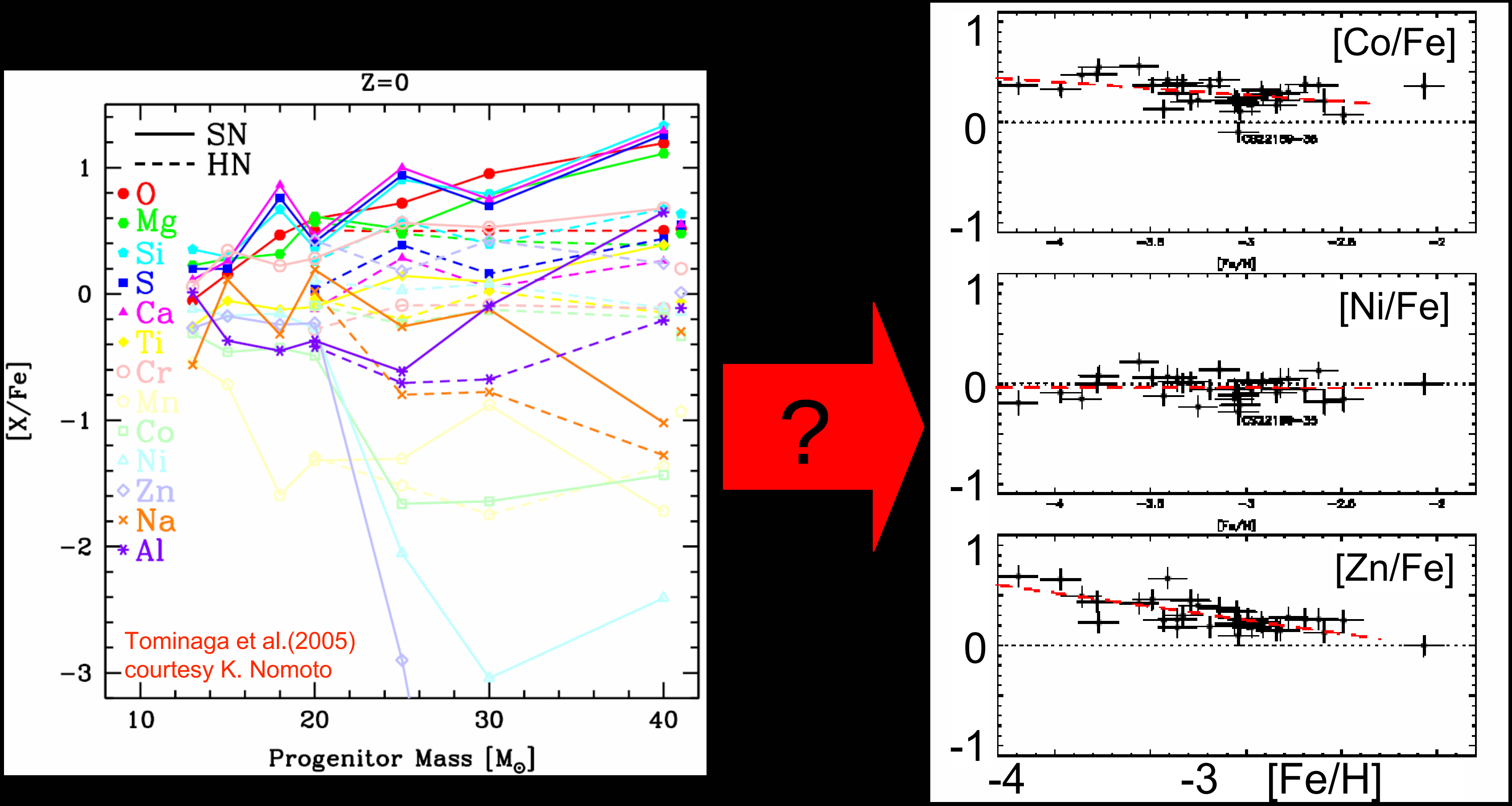
82% at [Fe/H] ≤ -2.5 show r-process enrichment

HERES Survey - Barklem et al. (2005)

Abundance Patterns in Population II Galactic halo stars:

- $>10^3$ of metal-poor stars from decades of surveys, more to come.
- high-res spectra from VLT and Keck show elements in well-defined but often poorly understood trends in [X/Fe] and r-process.
- This rich dataset, a gift of nature by way of the observers, deserves our attention apart from our desire to understand the IMF.

A Fundamental Disconnect



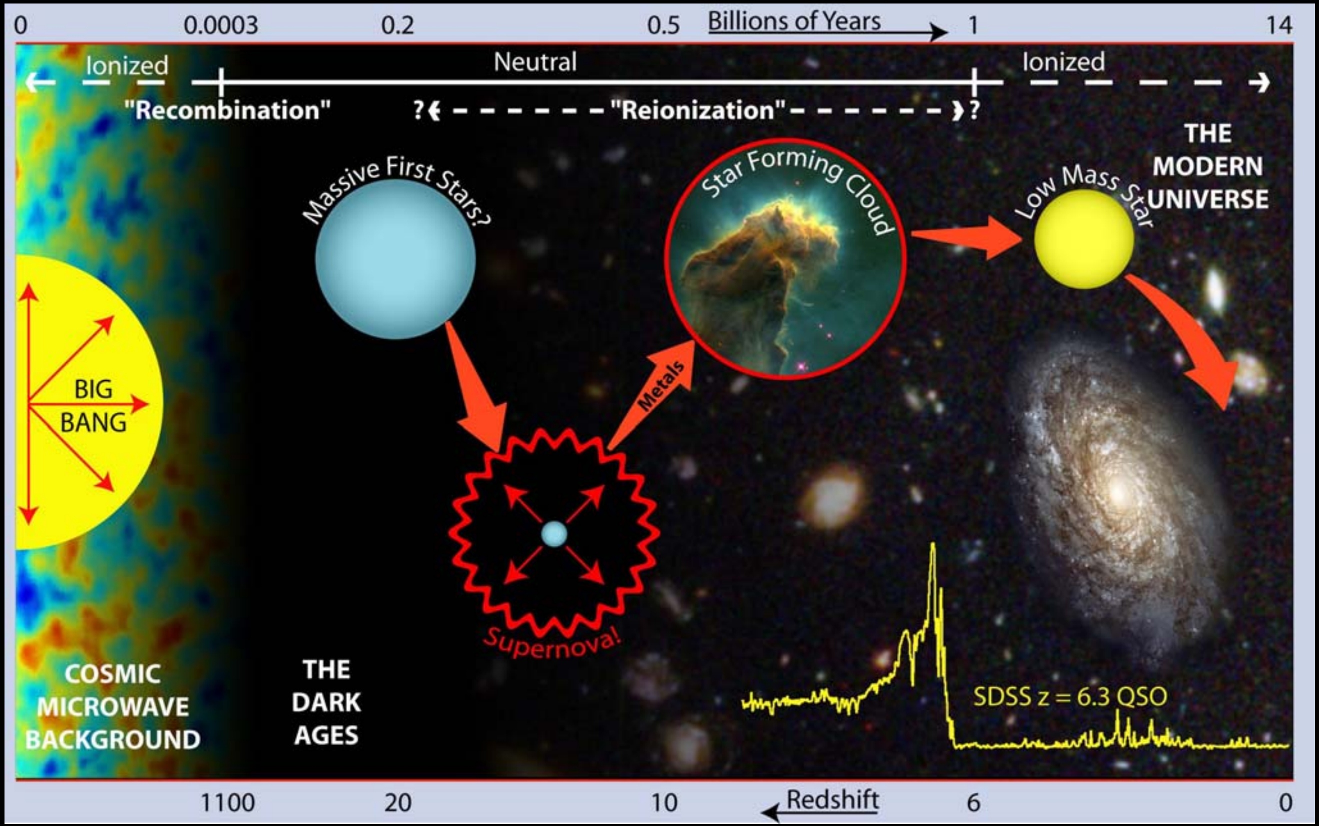
Tominaga et al.(2005)
courtesy K. Nomoto

But we know that each Pop II star is an **average over mass and metallicity**, so we need to know M and [Fe/H] for all progenitors to properly apply yields.

Also, despite diligent theoretical efforts, there is still no “basis set” of yields.

We therefore need a quantitative model that maps intrinsic SNe yields to the data, in the proper astrophysical context of early chemical evolution.

New Framework Needed to Address Rich Data



The proper context of early chemical evolution is the small pre-Galactic dark matter halos of $10^6 – 10^7$ $M_\odot$ at z > 10.

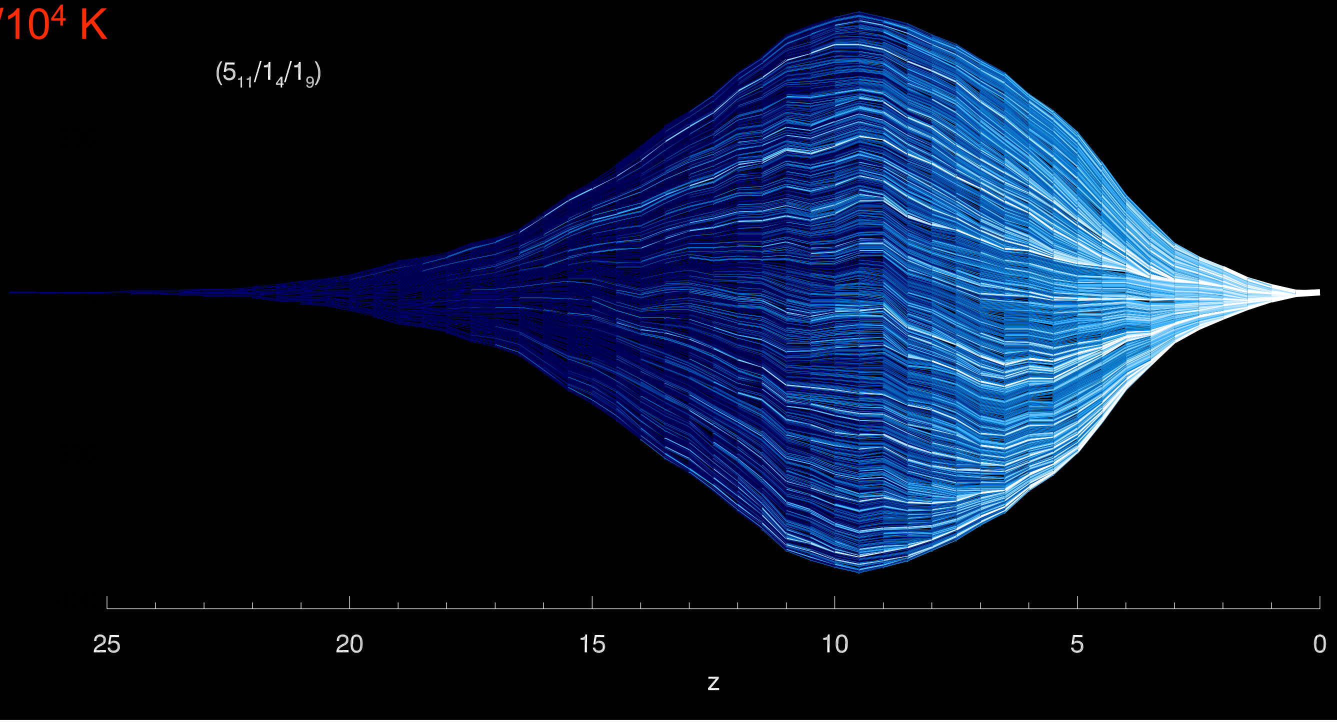
These halos and their stars probably also initiate reionization.

We can therefore study early chemical evolution and reionization together, by following chemical evolution in hierarchical models of galaxy formation.

A New Synthesis of Chemical Evolution & Structure Formation

Tumlinson 2005, astro-ph/0507449

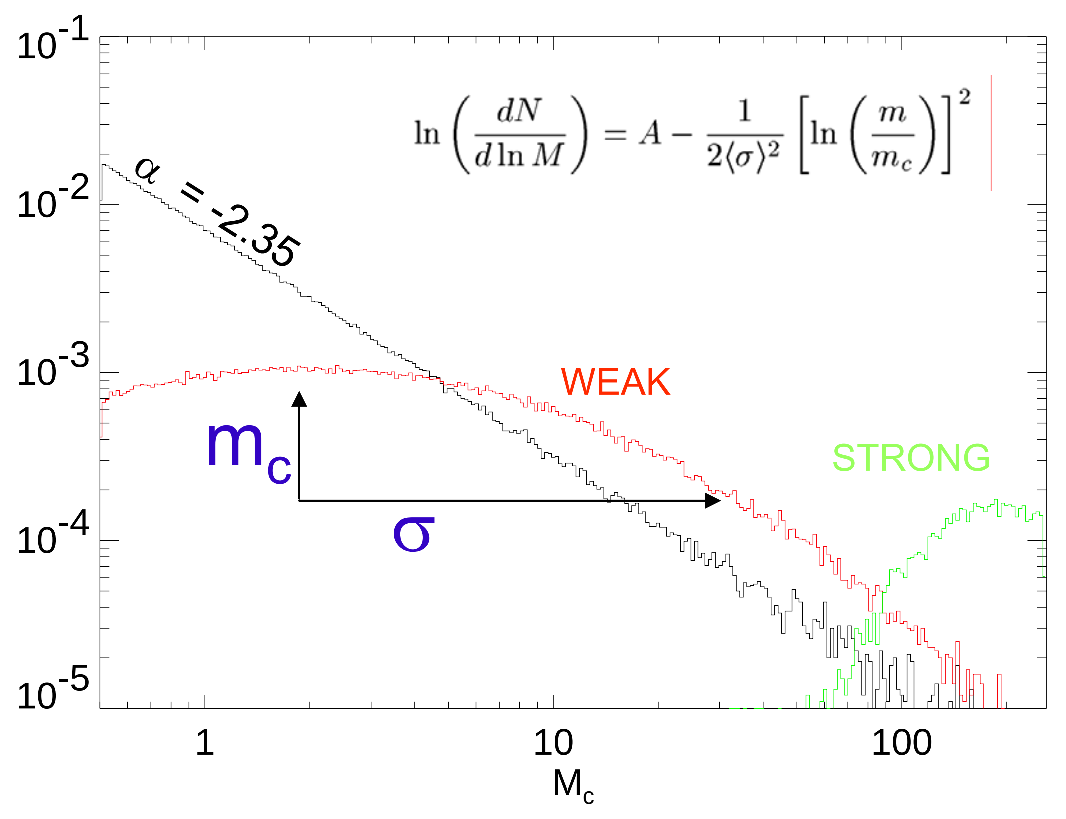
$5x10^{11}/10^{4}$ K



Tie chemical evolution to the larger picture of galaxy formation:

- The hierarchical theory of galaxy formation provides a natural approach to inhomogeneous chemical evolution, in the framework of *halo merger trees*.
- Each node in tree is a semi-closed box within which stellar birth, death, and ISM mixing evolve stochastically. Overall “mass” resolution $T_{vir} = 10^3$ K.
- Best of all, these “boxes” can be modeled as individual galaxies for direct comparisons to data at high redshift – this is also a SAM code.

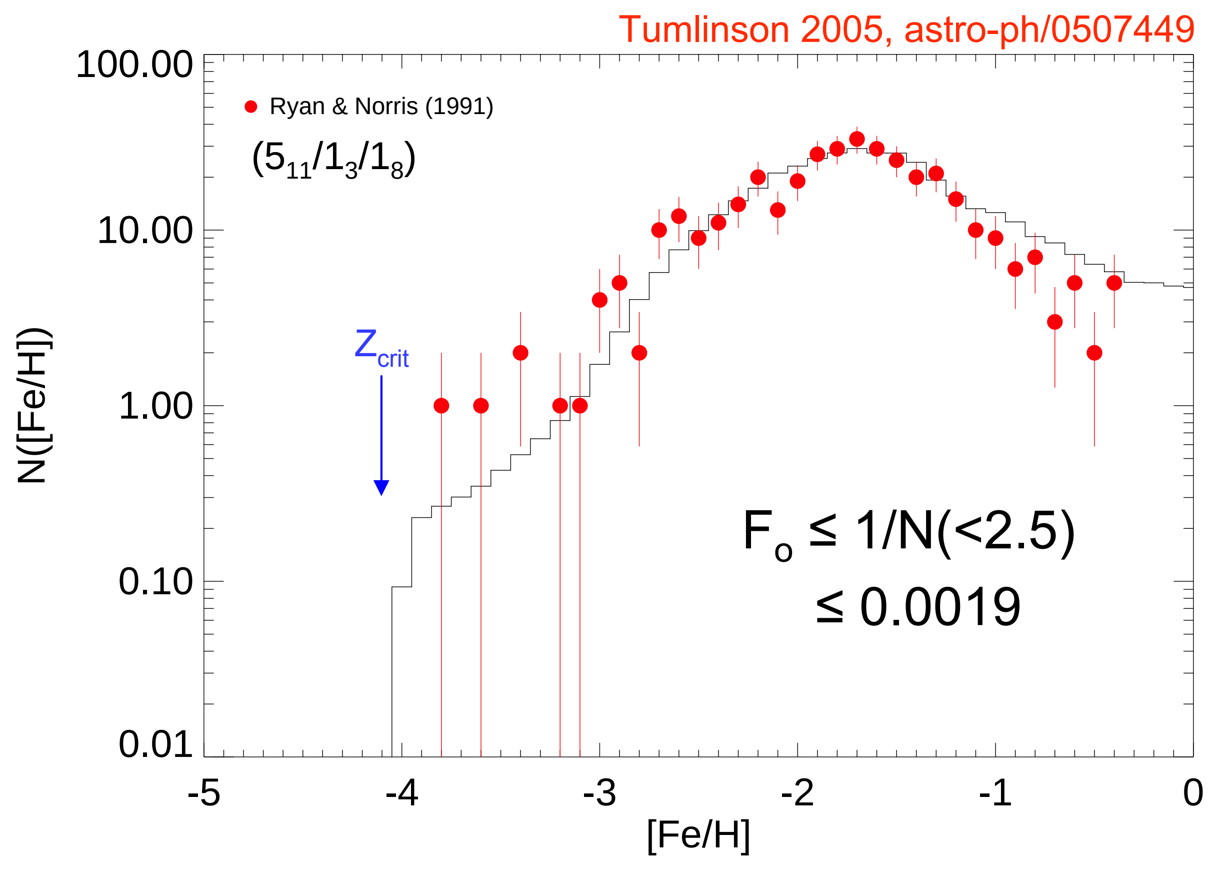
Key Component: The Log-Normal IMF



A Simple Parameterization:

- Allows more complex behavior than a power-law, with only one more parameter.
- Well-suited to the wide range of mass and shapes possible in primordial gas.

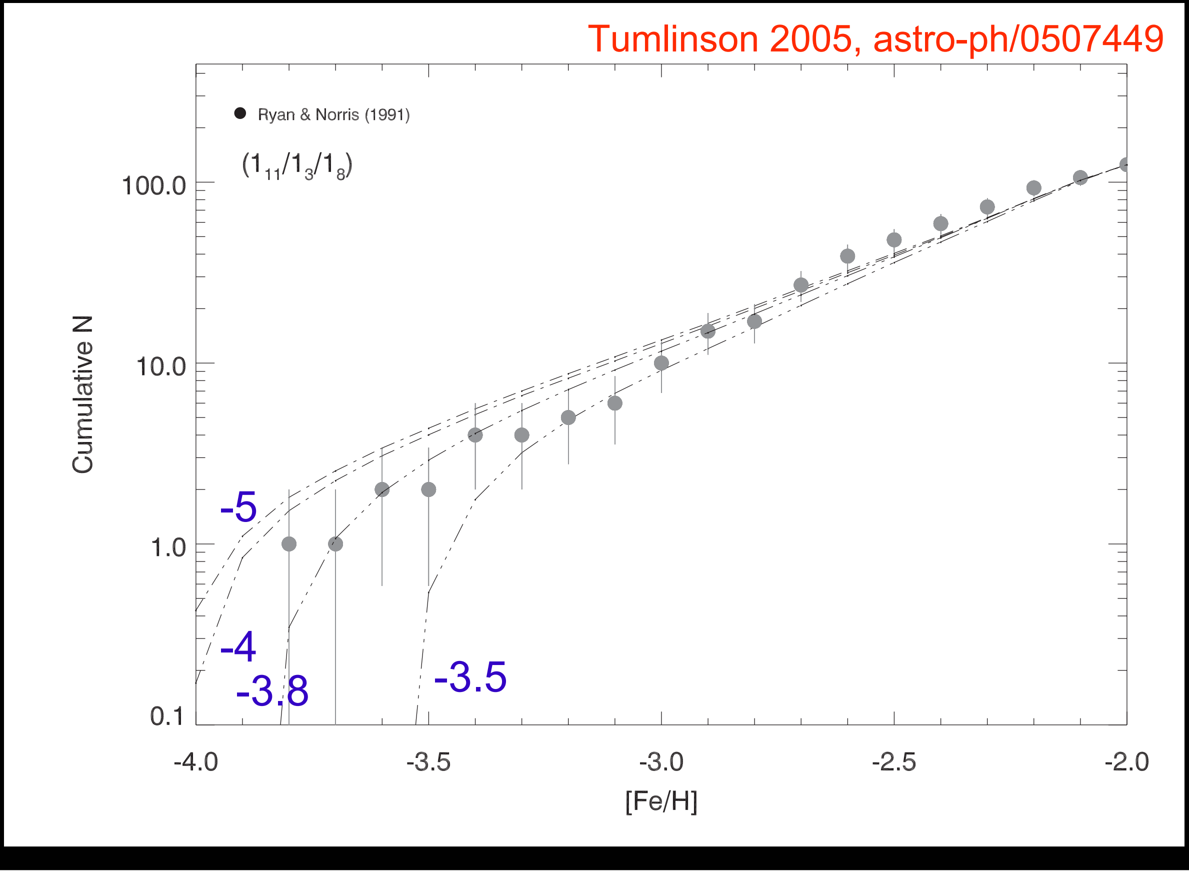
Key Result: The Metallicity Distribution Function (MDF)


Tumlinson 2005, astro-ph/0507449

The Model Easily Matches A Key Observable:

- The distribution of halo star metallicities [Fe/H] (~300 stars in MDF from Ryan & Norris 1991; >10000 to come soon from SDSS-SEGUE).
- No Z=0 star has been found, so Z = 0 fraction $F_o = 1/N(<2.5) = 0.0019$.

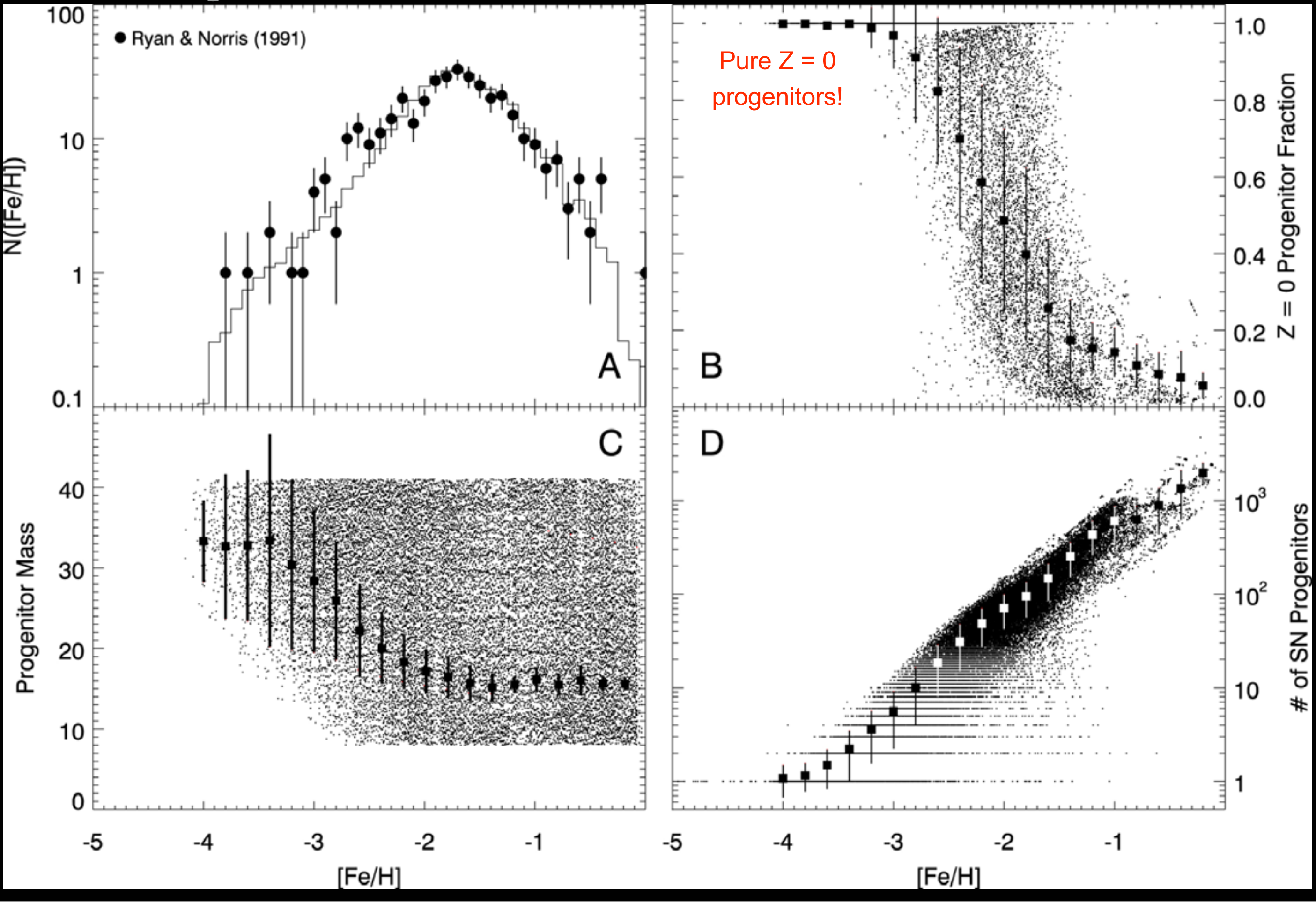
Is the Critical Metallicity Detected?



Looking for Z_{crit} in the Cumulative MDF:

- Z_{crit} controls the low-metallicity cutoff of the cumulative MDF.
- $Z_{crit} = 10^{-5}$ to $10^{-3.5}$ is consistent with the MDF data.
- Without detection of a sharp “feature”, Z_{crit} is ~ the lowest detected metallicity.

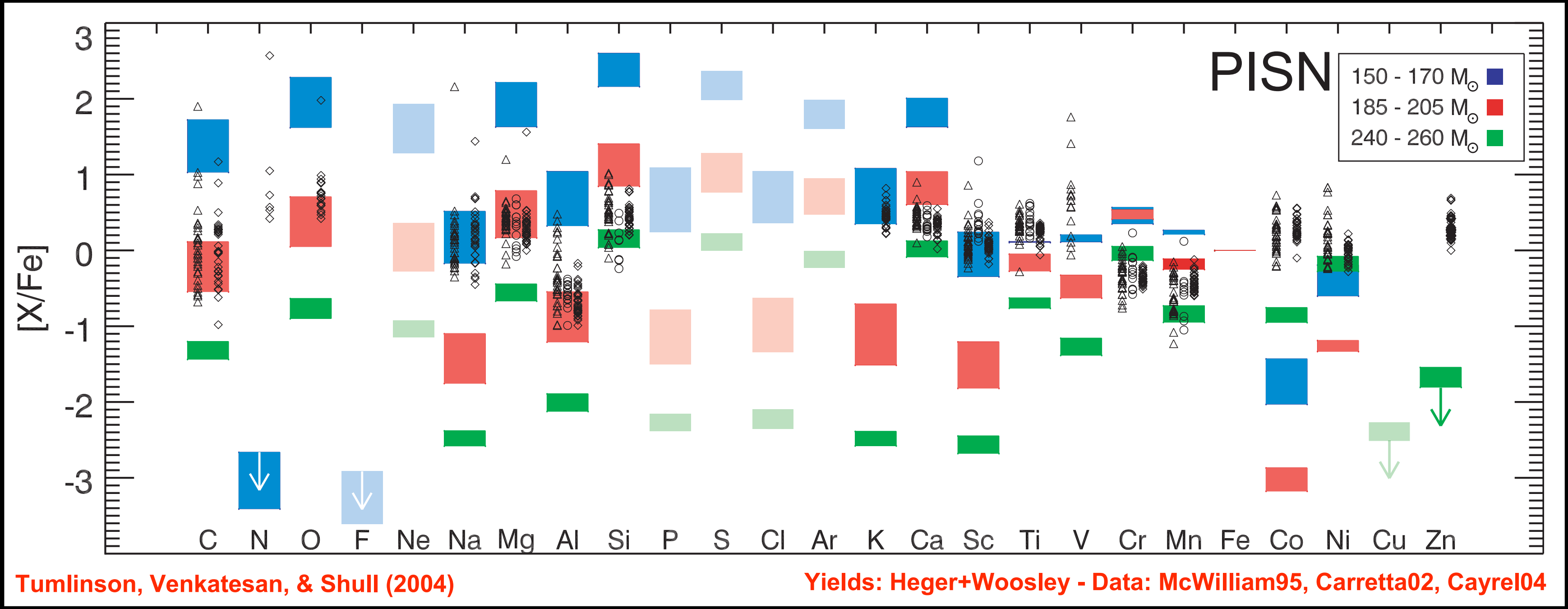
Unraveling Chemical Evolution, “One Star at a Time”



Detailed Chemical Evolution in the Context of Hierarchical Galaxy Formation:

- For a given model, the model follows self-consistently the metallicity and mass distribution of progenitors that produced a Pop II star.
- Below [Fe/H] = -3, all supernova progenitors of Pop II stars are metal-free, so we can compare [Fe/H] < -3 yields directly with theory, and address IMF.

VMS and Nucleosynthesis



Tumlinson, Venkatesan, & Shull (2004)

Yields: Heger+Woosley - Data: McWilliam95, Carretta02, Cayrel04

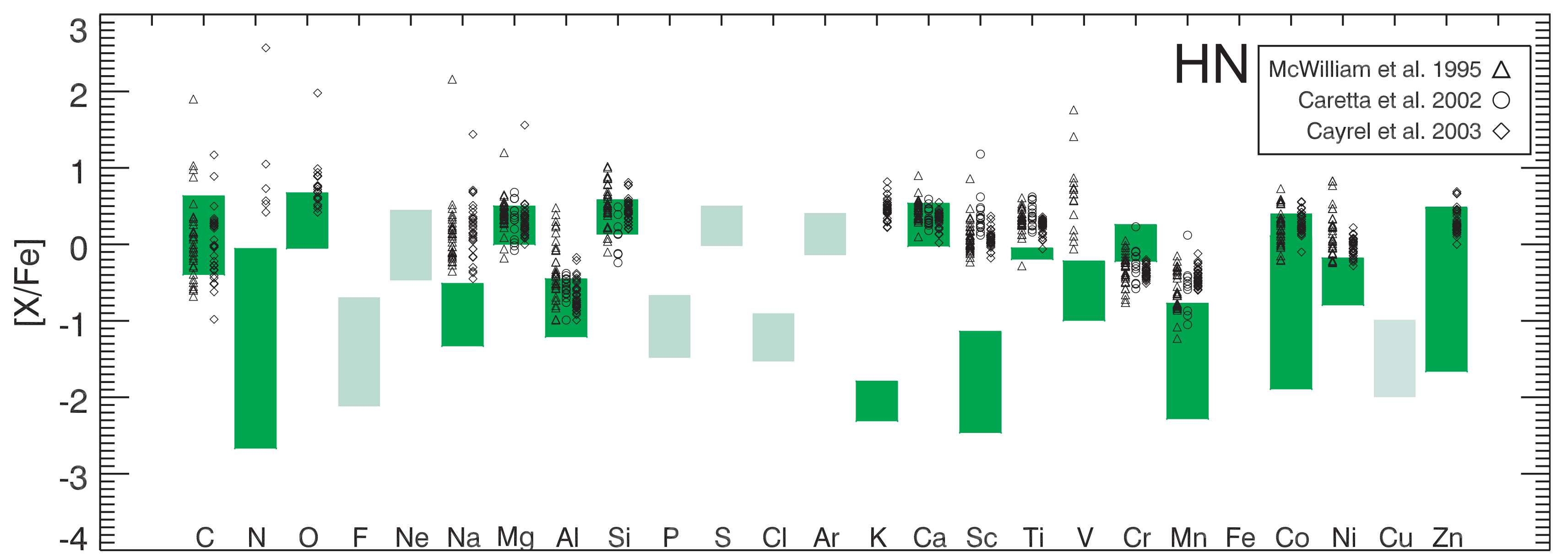
<u>Yields of individual VMS/PISN compared to Galactic Pop II stars:</u>

- STRONG: contradicted by r-process elements down to < -3.

- WEAK: Possibly excluded by poor match to Fe-peak elements and extreme odd-even effect, esp. with one progenitor.

Should conservatively allow less than ½ of Fe from VMS.

Hypernovae and Nucleosynthesis



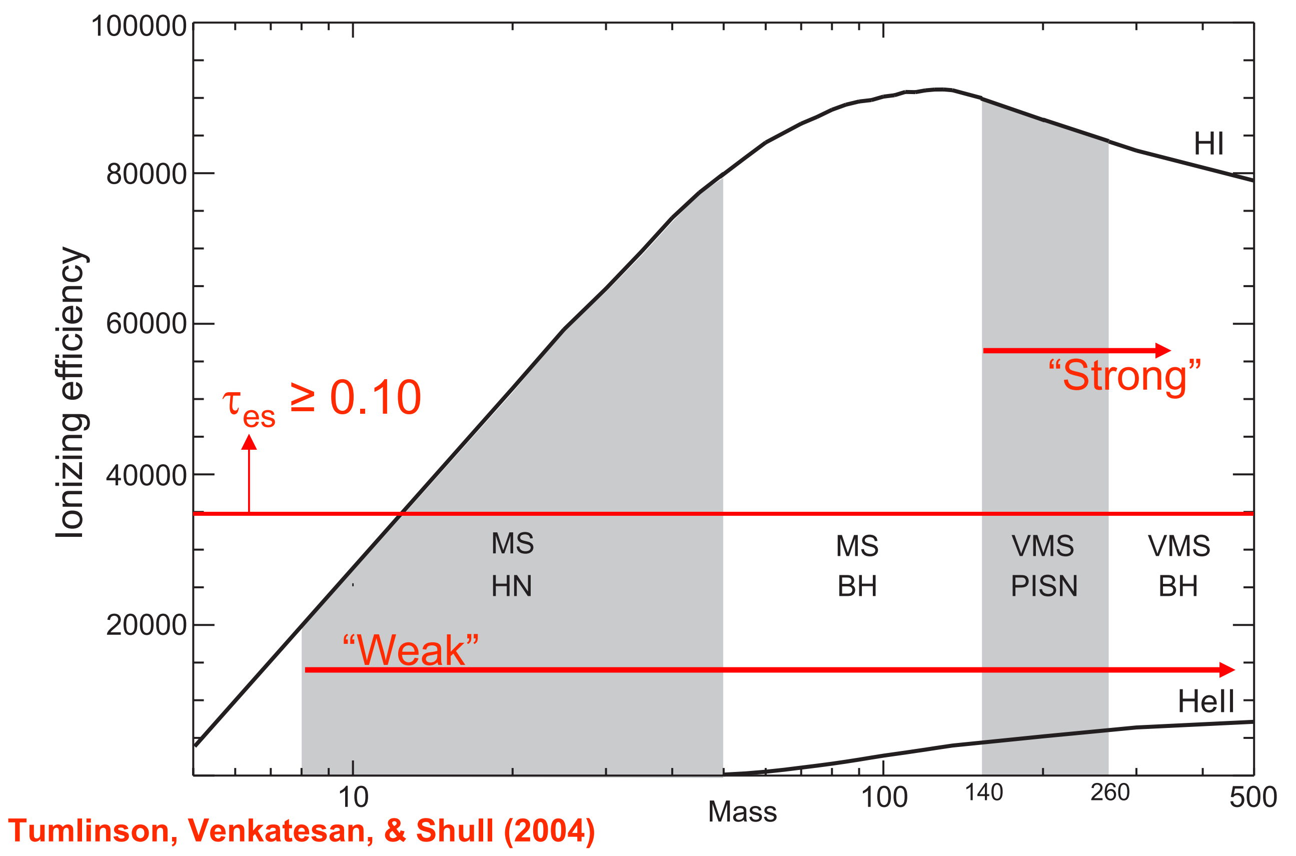
Tumlinson, Venkatesan, & Shull (2004)

Yields: Umeda+Nomoto04 - Data from McWilliam95, Carretta02, Cayrel04

A *Possible* Solution: Energetic “Hypernovae” in the First Generation:

- Metal-free stars with M = 10 – 50 $M_\odot$ might have exploded as “hypernovae” (E_{51} = 1-100) instead of PISN (Umeda+Nomoto2004).
- Yields match better than PISN, and can also create *r*-process elements from 8 – 40 $M_\odot$ progenitors. (Also possible GRBs!).

Reionization and The First Star Mass Function

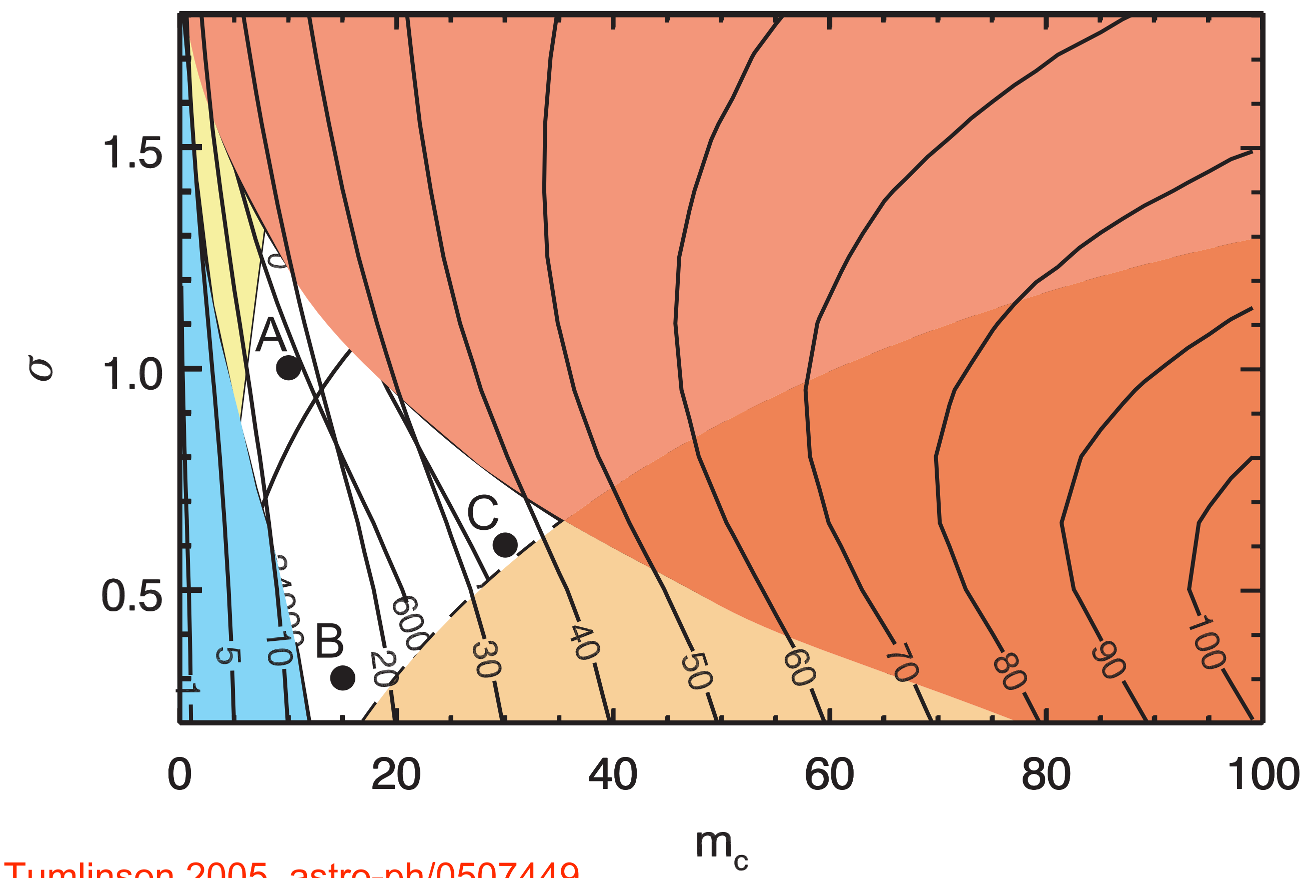


Tumlinson, Venkatesan, & Shull (2004)

Ionizing Efficiency is Key to Producing High Optical Depth to Reionization:

- WMAP: $\tau_{es} = 0.17^{+0.08}_{-0.07}$, SDSS LSS+WMAP: $\tau_{es} = 0.12^{+0.08}_{-0.06}$
- Ionizing efficiency (γ_0) increases to ~ 120 $M_\odot$, then declines.
- Characteristic γ_0 > 34000 required for conservative limit on IMF.

Primary Result: Constraints on Primordial IMF

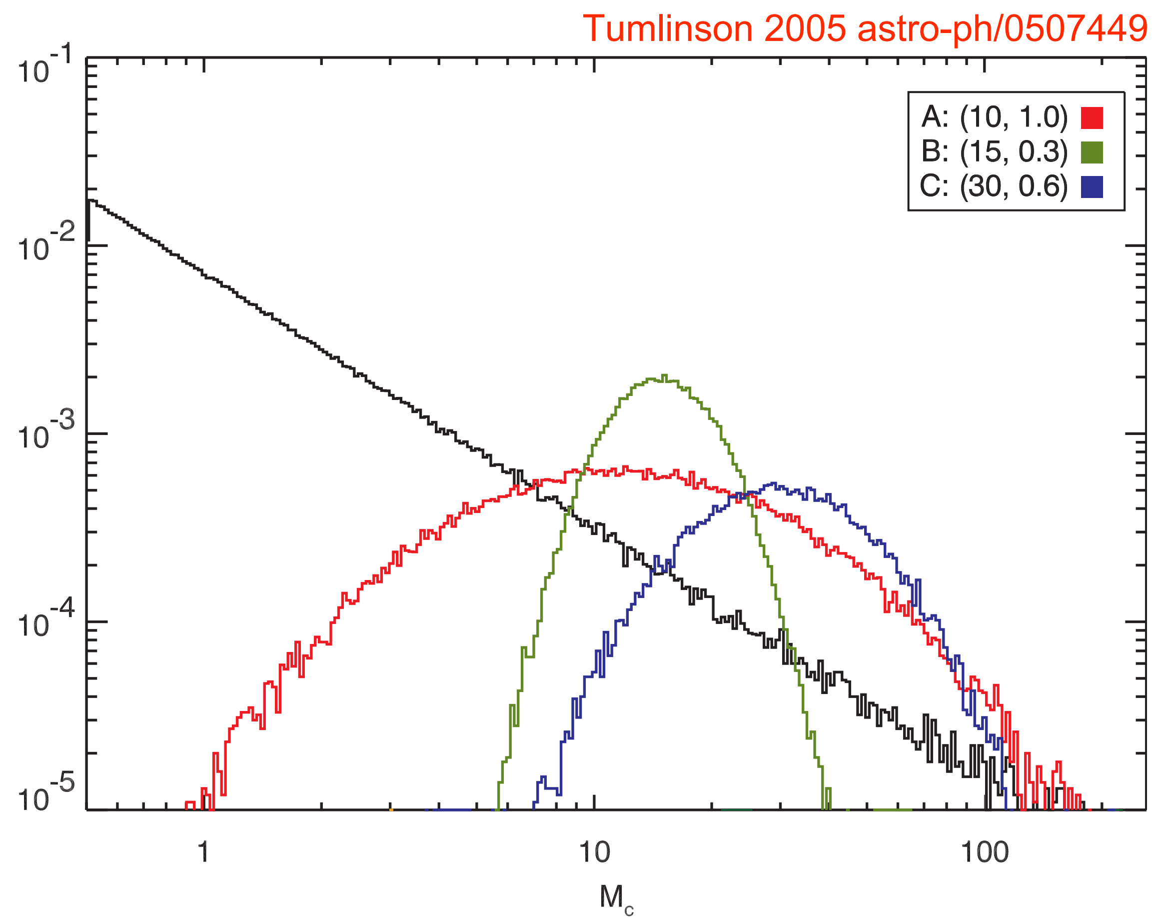


Tumlinson 2005, astro-ph/0507449

Joint Constraints on IMF from Halo MDF, Pop II Stars, and Reionization:

- Low-metallicity IMF is confined to the unshaded region, with <M> = 10 – 42 $M_\odot$
- This IMF does not overproduce Pop III stars (F_0) or VMS, and it produces enough ionizing photons for reionization.
- Encouragingly close to Tan+McKee ~20 $M_\odot$ radiation feedback-limited mass.

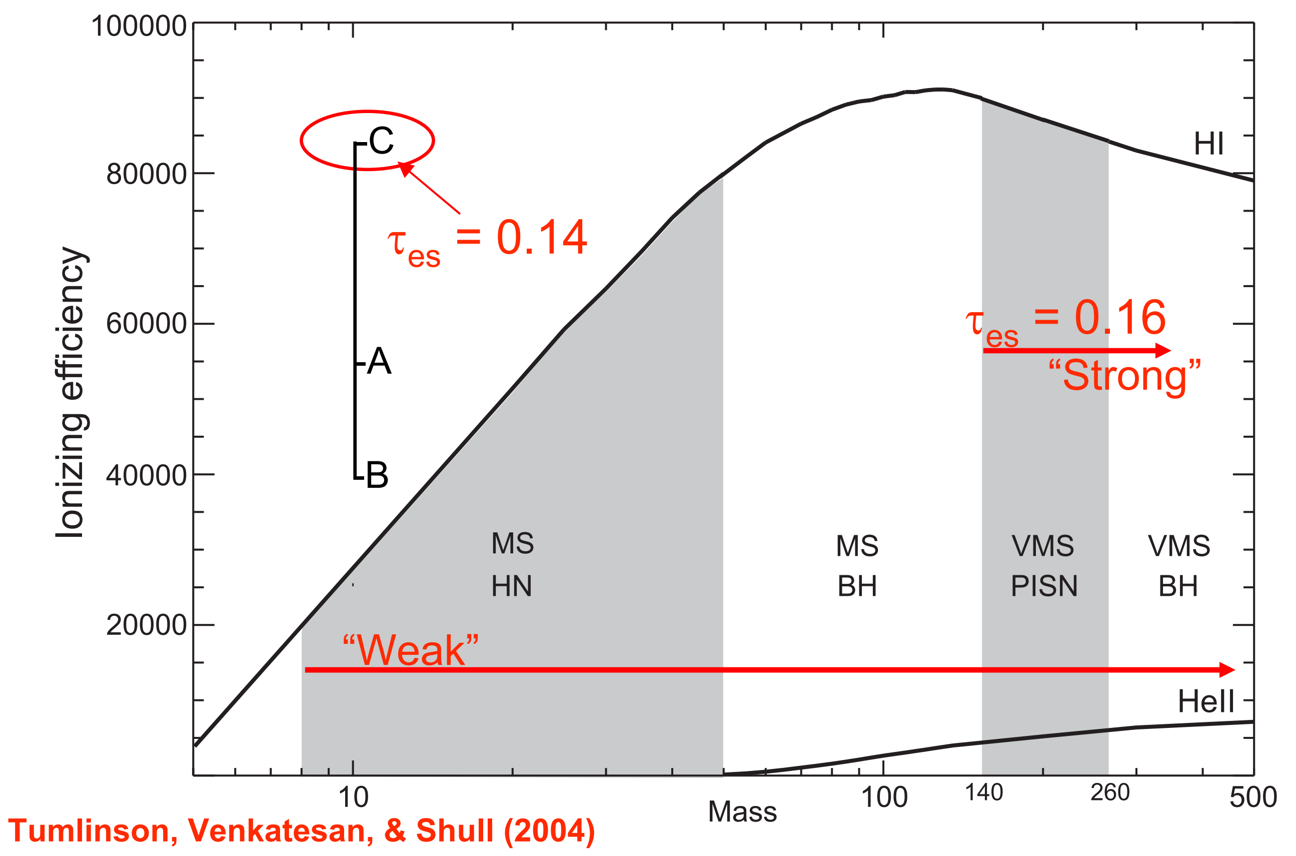
The First Stars IMF?



<u>IMF Cases Derived from Chemical Evolution and Reionization:</u>

- A single IMF can meet the halo MDF constraint, produce enough ionizing photons to yield $\tau_{es} \sim 0.1$, and not overproduce VMS.
- More work is needed to map out the whole parameter space and test these against high-z galaxies and more Pop II stars.

Reionization and The First Star Mass Function



Tumlinson, Venkatesan, & Shull (2004)

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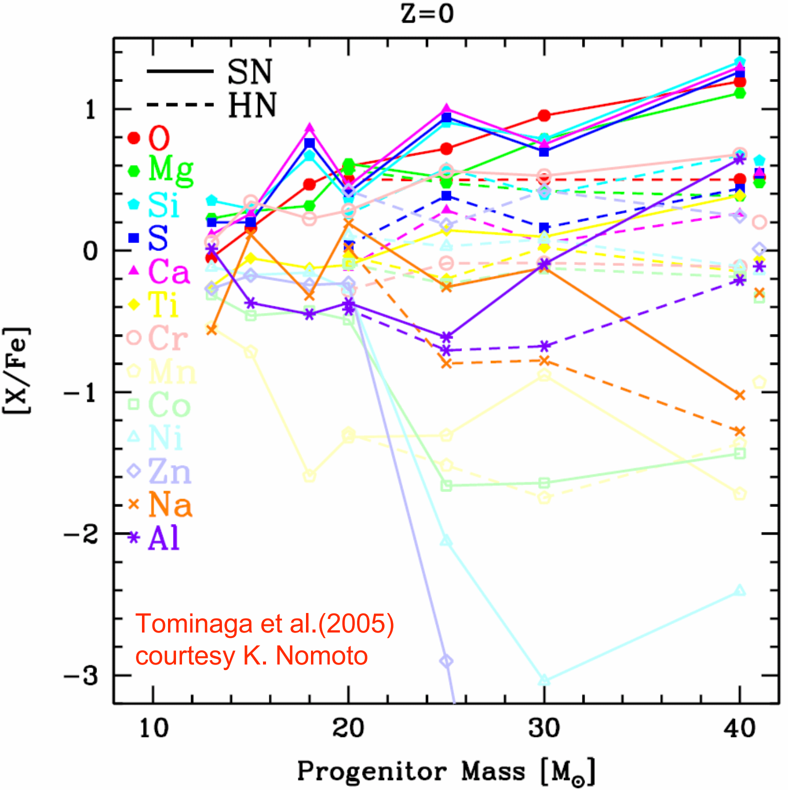
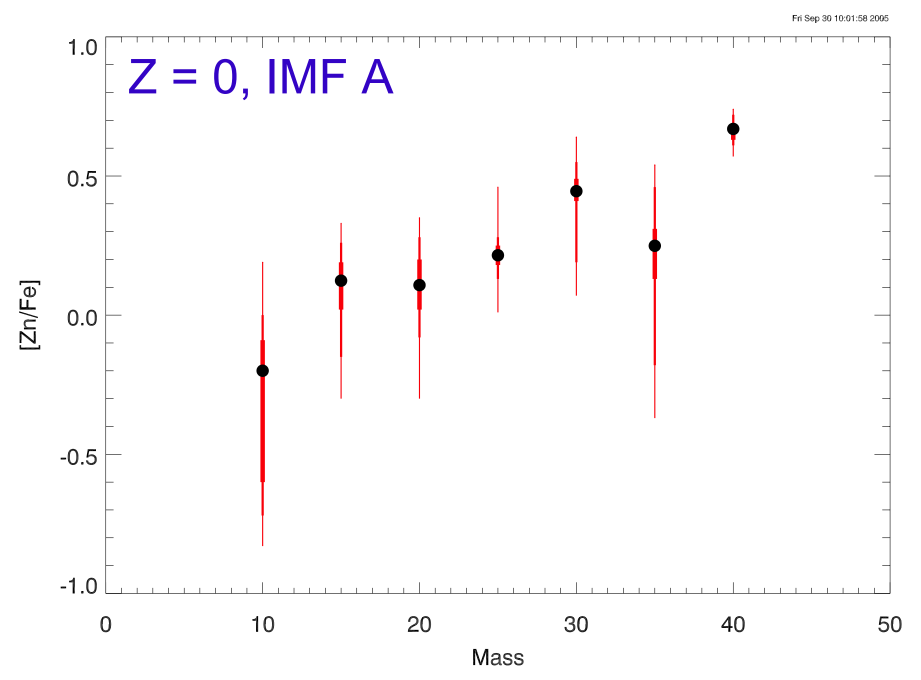
- WMAP: $\tau_{es} = 0.17^{+0.08}_{-0.07}$, SDSS LSS+WMAP: $\tau_{es} = 0.12^{+0.08}_{-0.06}$
- Ionizing efficiency (γ_0) increases to ~ 120 $M_\odot$, then declines.
- Characteristic γ_0 ~ 40000 – 50000 from $T \geq 10^3$ K halos needed to give τ_{es} ~ 0.1.
- IMF cases A-C, which match the nucleosynthesis data, also give reasonable τ_{es}.

Chemical Evolution Approaches the "Precision Era"





Detailed Yields for Metal-Free Stars:

- These are the yields that best map the stellar histories in the chemical evolution model to data on 35 stars from Cayrel et al. (2004).
- These results offer the most direct comparison that the data will allow for comparing to *ab initio* SN models (i.e. Heger, Nomoto).
- Detailed empirical yields will soon be available for a wide range of progenitor mass and metallicity, and will improve as data grows.

Conclusions

- First-star IMFs that are too top-heavy are disfavored by the existing data on halo abundances. The preferred mean mass is 10 – 40 $M_\odot$. Z_{crit} is probably not yet constrained.

- The “best-fit” IMF, inferred from the halo abundances and theoretical yields, can also provide enough ionizing photons for reionization and the optical depth to CMB.

- The existing data and the new synthesis of theory offer critical guidance to planned surveys for Galactic archaeology and “near-field cosmology”.

- These surveys will push chemical evolution into the precision era and allow new tests for theories of Galaxy formation, early chemical evolution, and the first stars.

The Future of the Past Looks Bright

2005-2007

- Advance theory toward precision chemical evolution - "*one star at a time*".
- Programs directed at Pop II stars are priorities for many 8+ m telescopes.
- Serendipitous discoveries of early GRBs? (i.e. new one @ $z = 6.29$).
- New polarization data from WMAP (??) & Planck to improve τ_{es} constraints.

2007-2011

- SEGUE (10^4 stars) and WFMOS (10^6 stars) will constrain chem. ev.
- Theory to extract empirical chemical histories with rigorous methods.
- High-z emission line surveys will look for Lyα and He II λ1640.

2012+

- Launch of JWST will advance knowledge of early stars (± de-scope).
- Ground-based IR surveys (10 - 30 m) could open $z > 10$ to detailed study.
- Epoch of reionization may be open to 21 cm with large radio telescopes.

2020+

- High-res spectroscopy of resolved stars in other galaxies (= *next* HST).
- Degree-scale deep surveys of $z > 10$ galaxies (from space or ground).