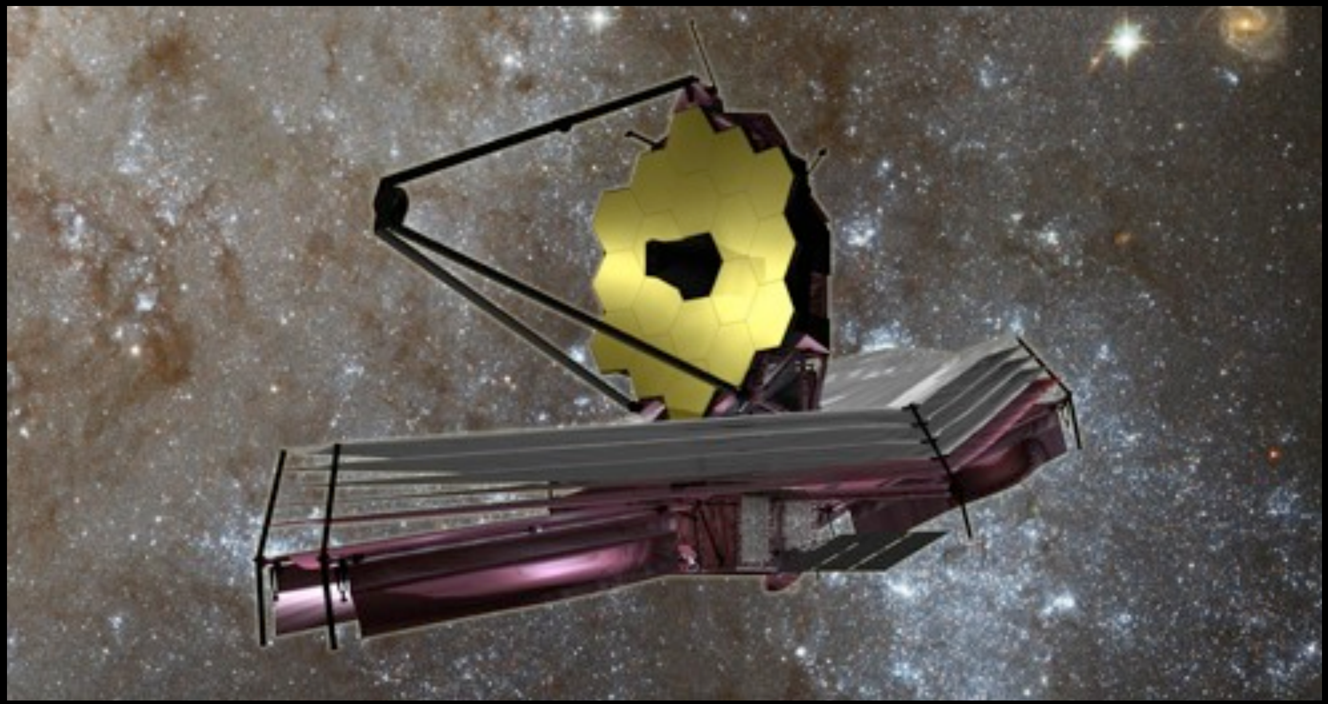
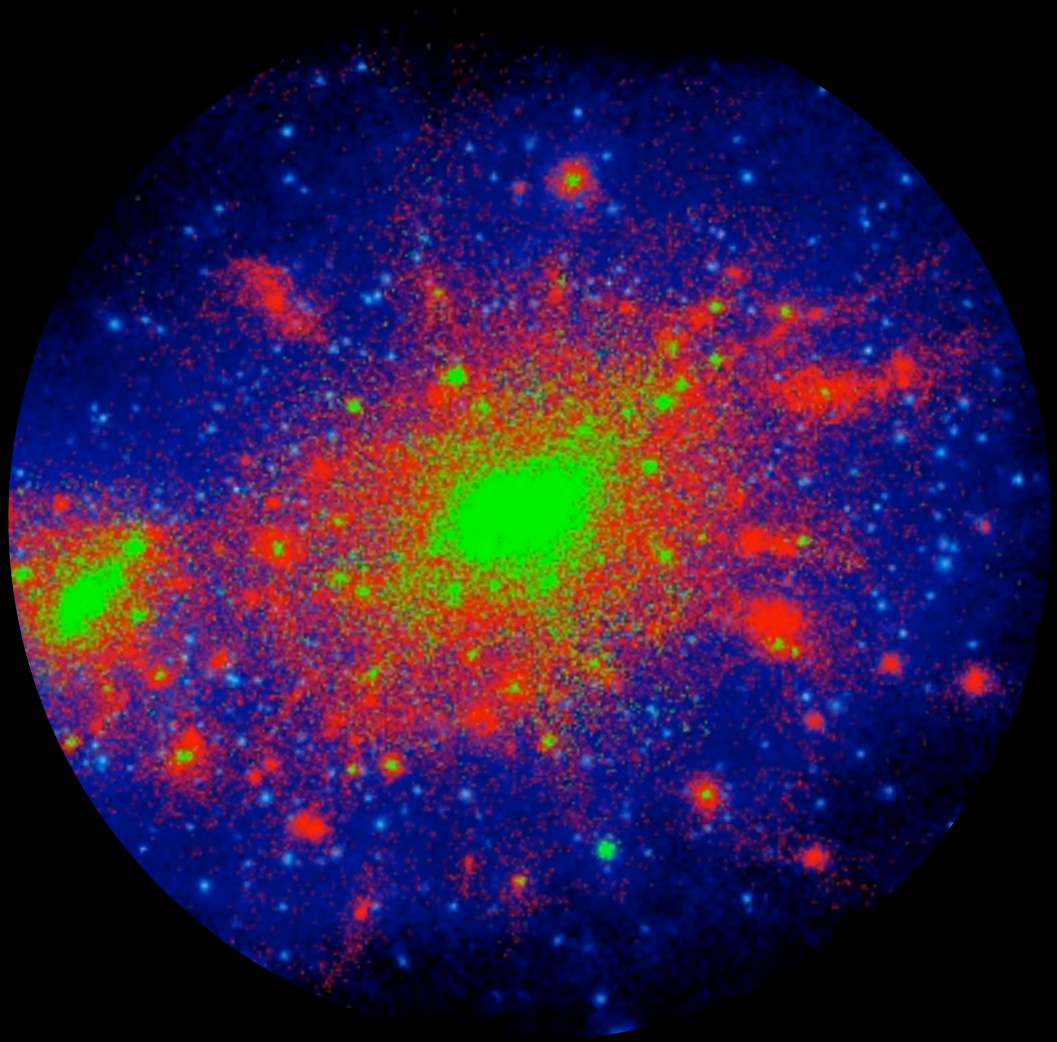
The First and Second Stars: How to Find Them and What to do About It

Three Big Ideas and Three Challenges





Jason Tumlinson

SPACE TELESCOPE SCIENCE INSTITUTE

March 9, 2010

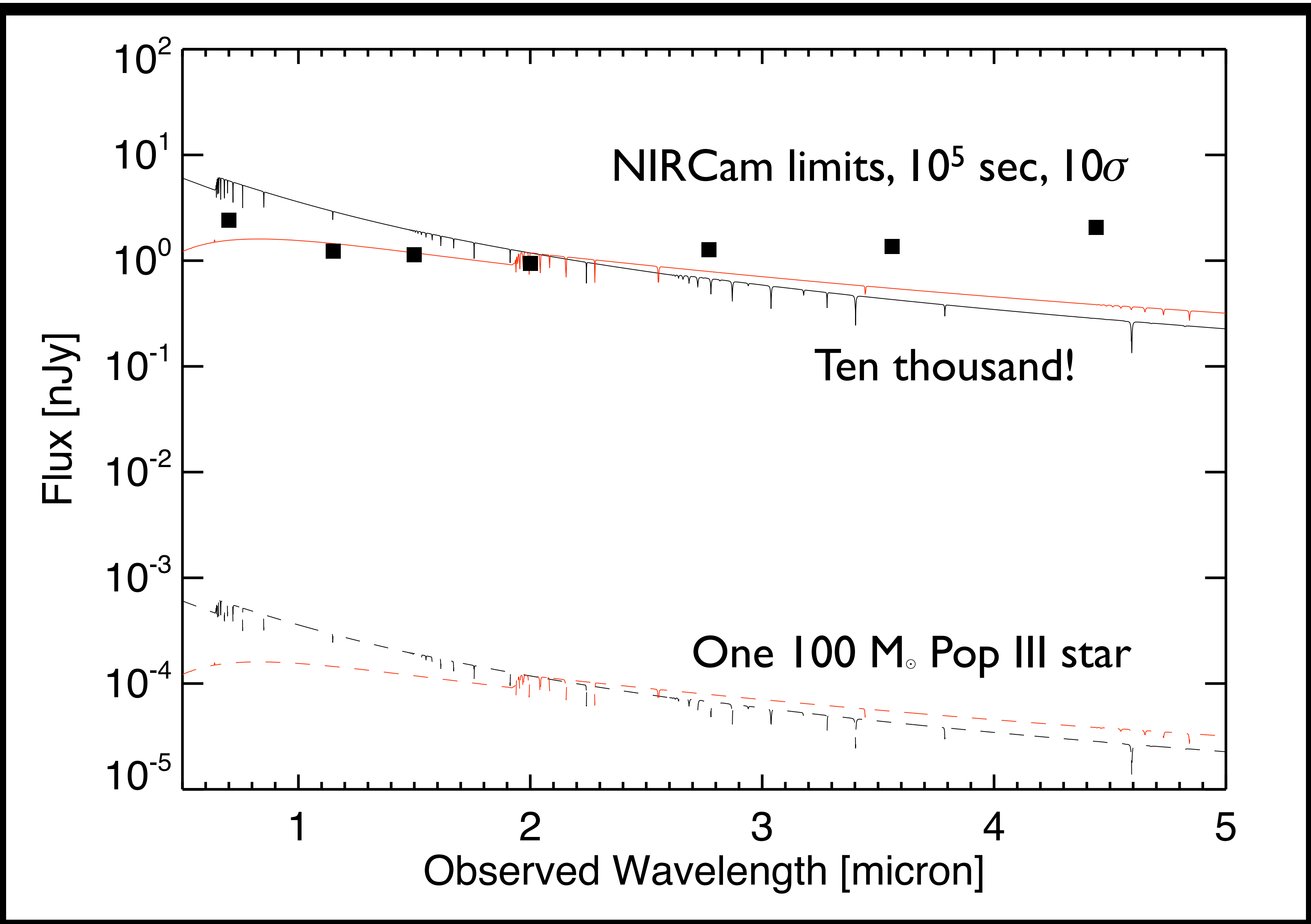
Motivating Questions:

How and when did Pop III change over to Pop II?

How did this transition depend on:
time?
metallicity?
environment?

Where should we look to find answers?

Is the transition visible where it occurred?



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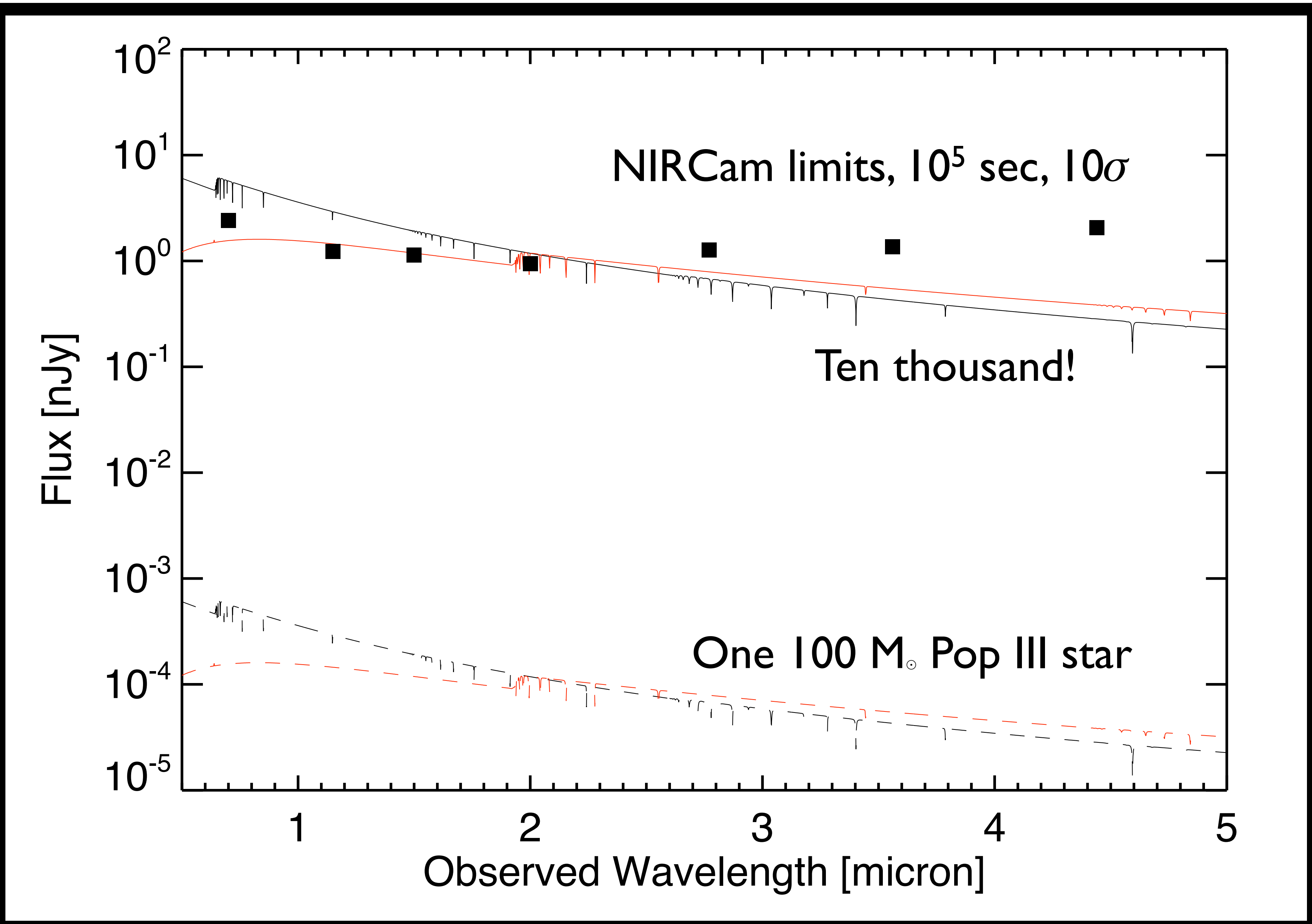
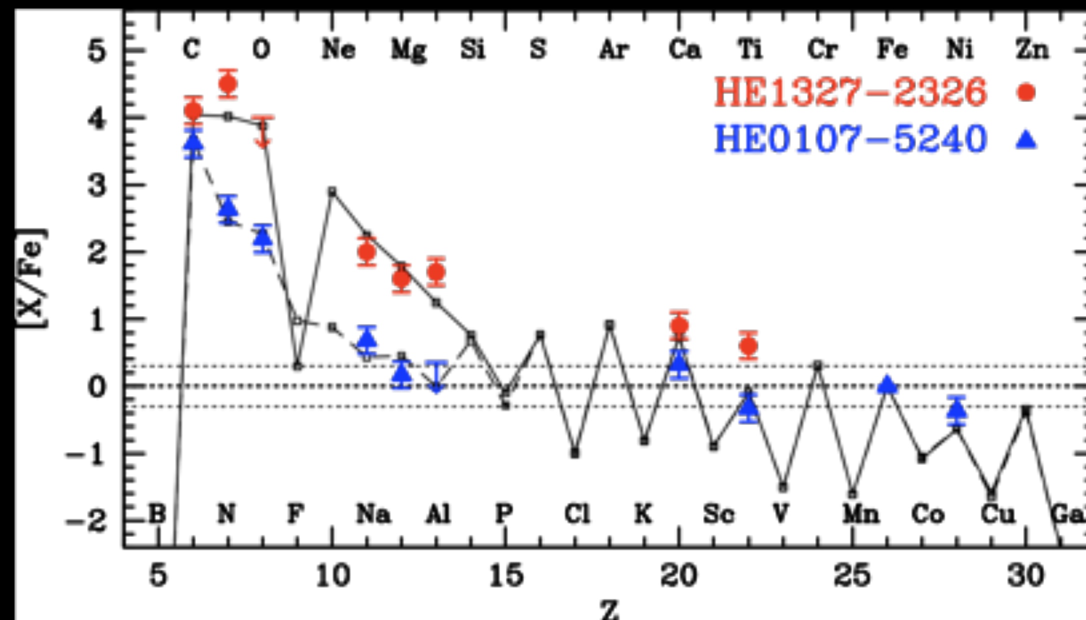
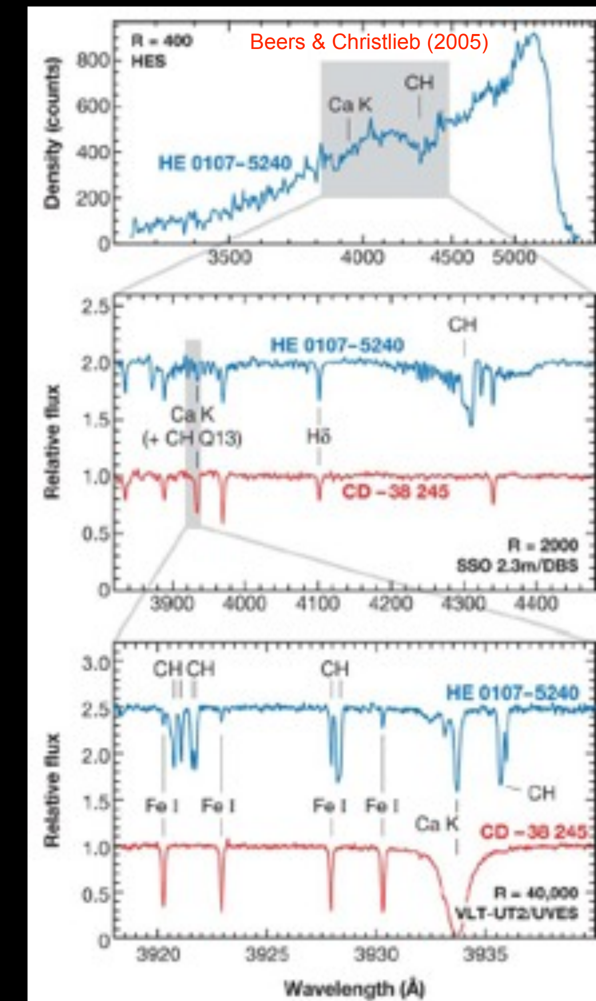


If our theory of the first stars is correct - one massive star per minihalo or small clusters in 10^4 K halos - it will be nearly impossible to detect them directly in the high-z Universe!

Now what?

First Big Idea: The First Galaxies and the Fossil Record

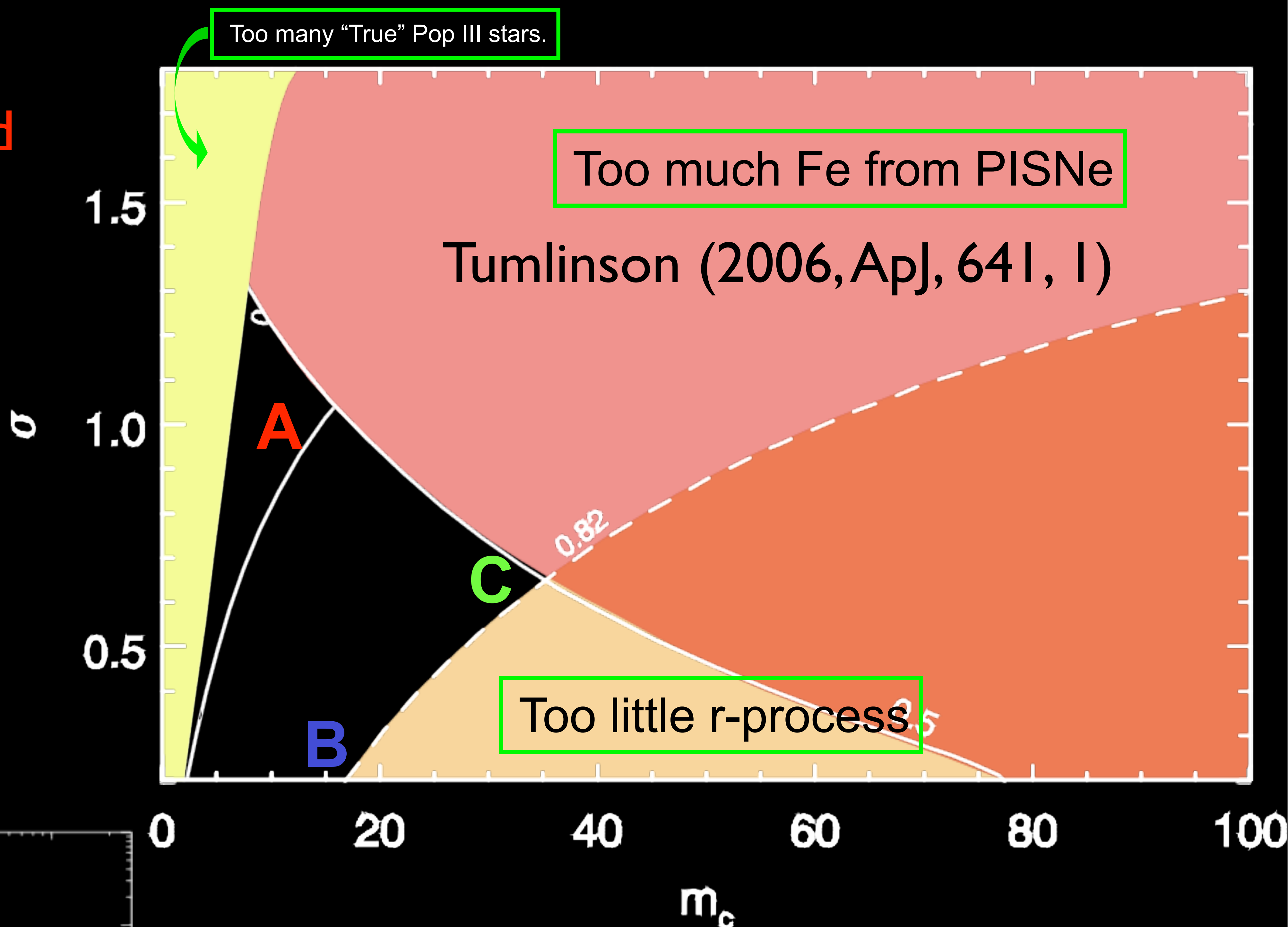




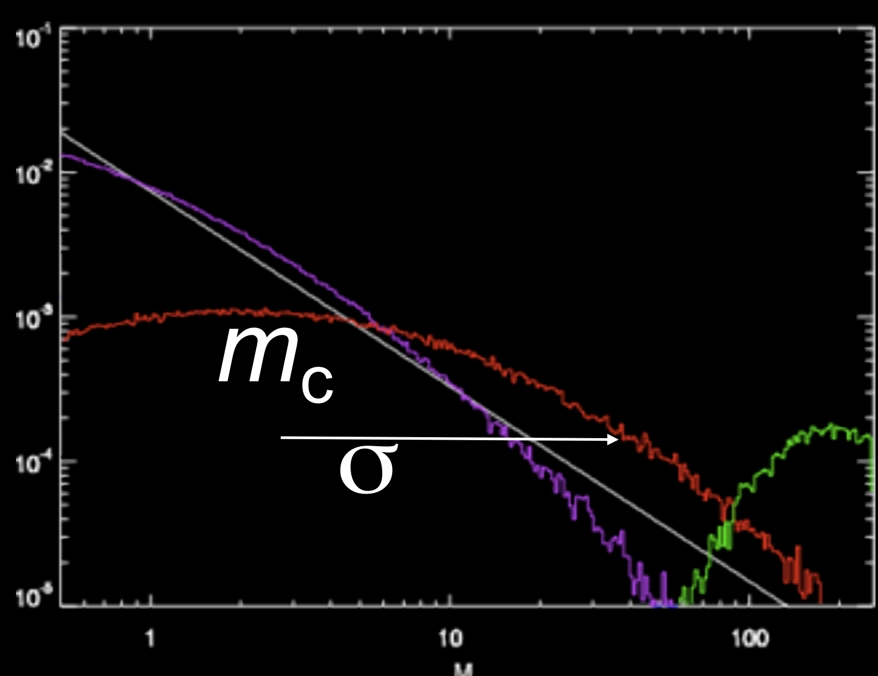
The "fossil record" of early chemical evolution is a burgeoning field about which we will hear much more.

But what if we could combine data from early star formation in situ AND data from "Galactic Archaeology" into a synthesis?

The Fossil Record of the Pop III IMF (so far)



PISNe are not needed to explain the observed chemical abundance of Milky Way halo stars.



Observed halo abundances fit in well with the emerging picture of "Pop III.2"; lower mass primordial stars, 10 - 100 M☉, formed in larger HD-cooled halos.

Lai et al.(2008) find ~ 10-20 M☉ is favored mass scale.

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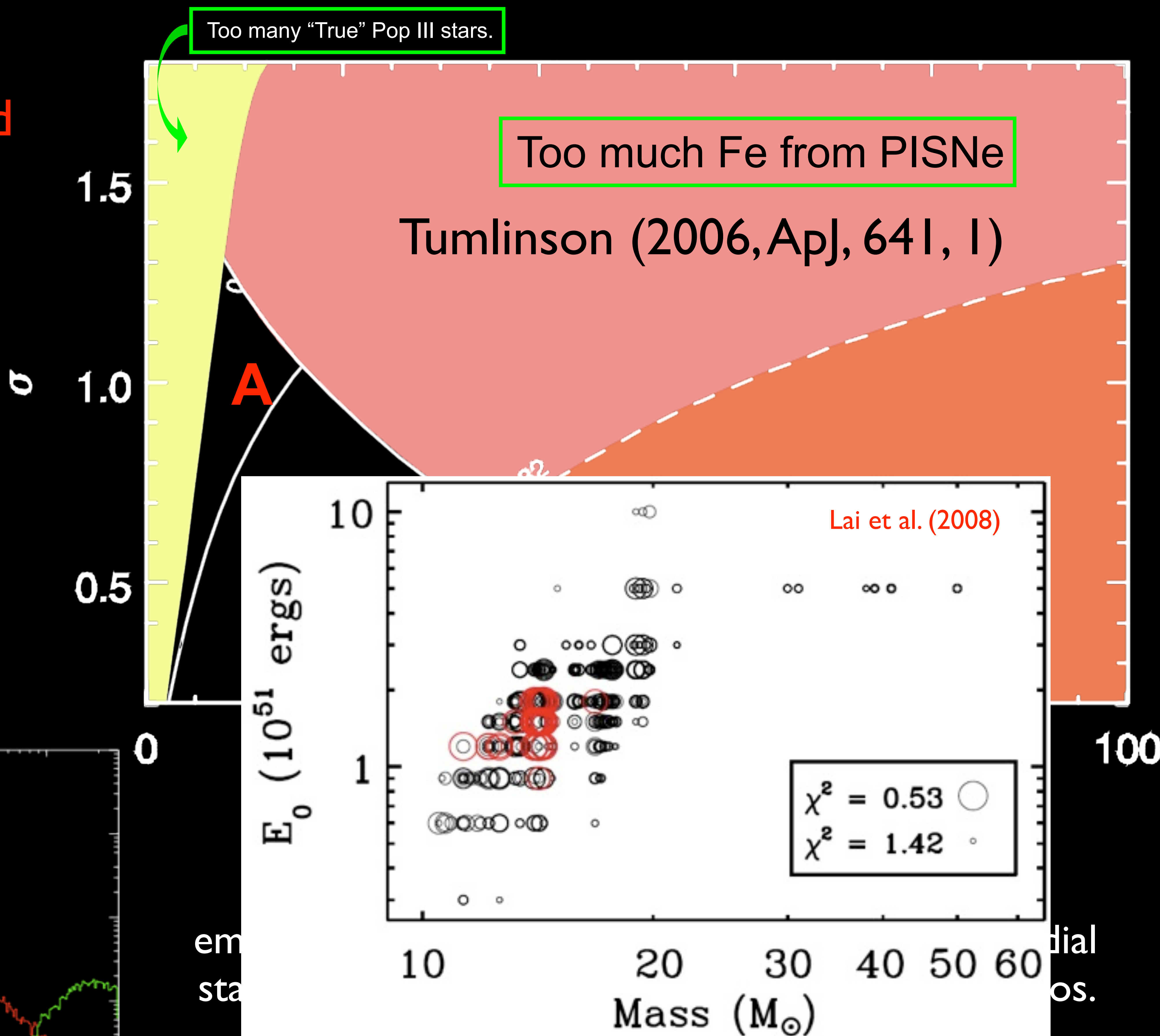

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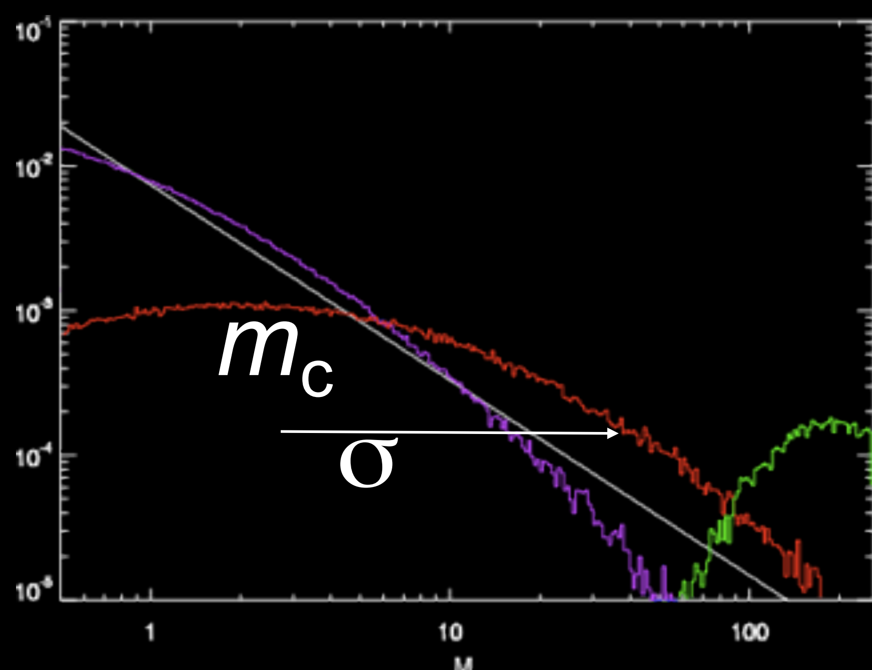
Lai et al.(2008) find ~ 10-20 $M_\odot$ is favored mass scale.



A New Framework for the Fossil Record

Models of CDM structure formation on their own predict that the earliest "high σ peaks" are centrally concentrated in the final halo.

To assess the consequences of this result on the stellar populations, we must make a global, CDM-based model.

Tumlinson (2010, ApJ, 708, 1398)

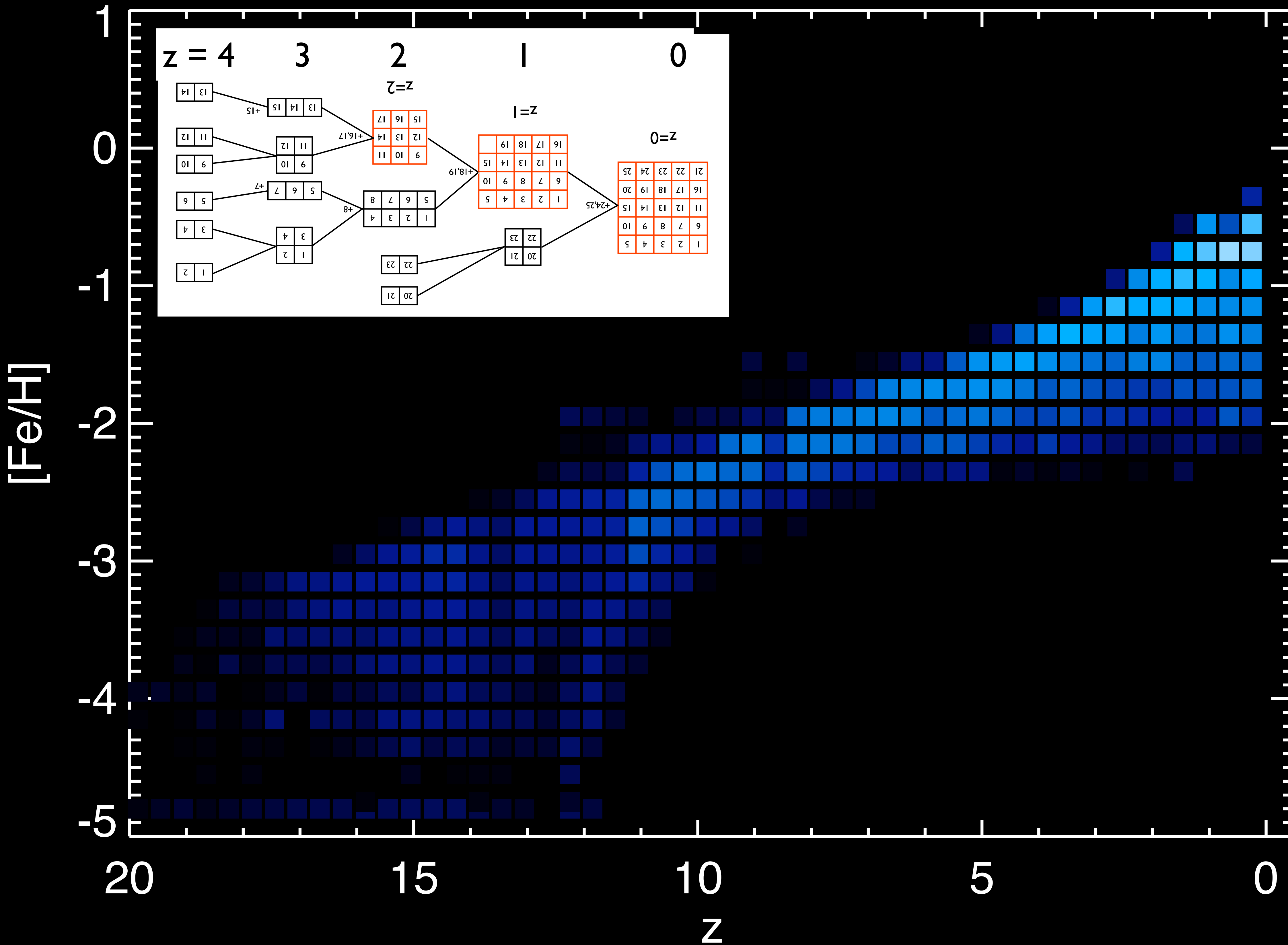
Fine Print:

Gadget2 simulations, $M_{vir} \sim 1.5\times10^{12}\ M_\odot$, $M_{DM} = 2.6\times10^5\ M_\odot$, 6-8 million particles inside $R_{vir} \sim 380$ kpc, last major merger > 10 Gyr ago.

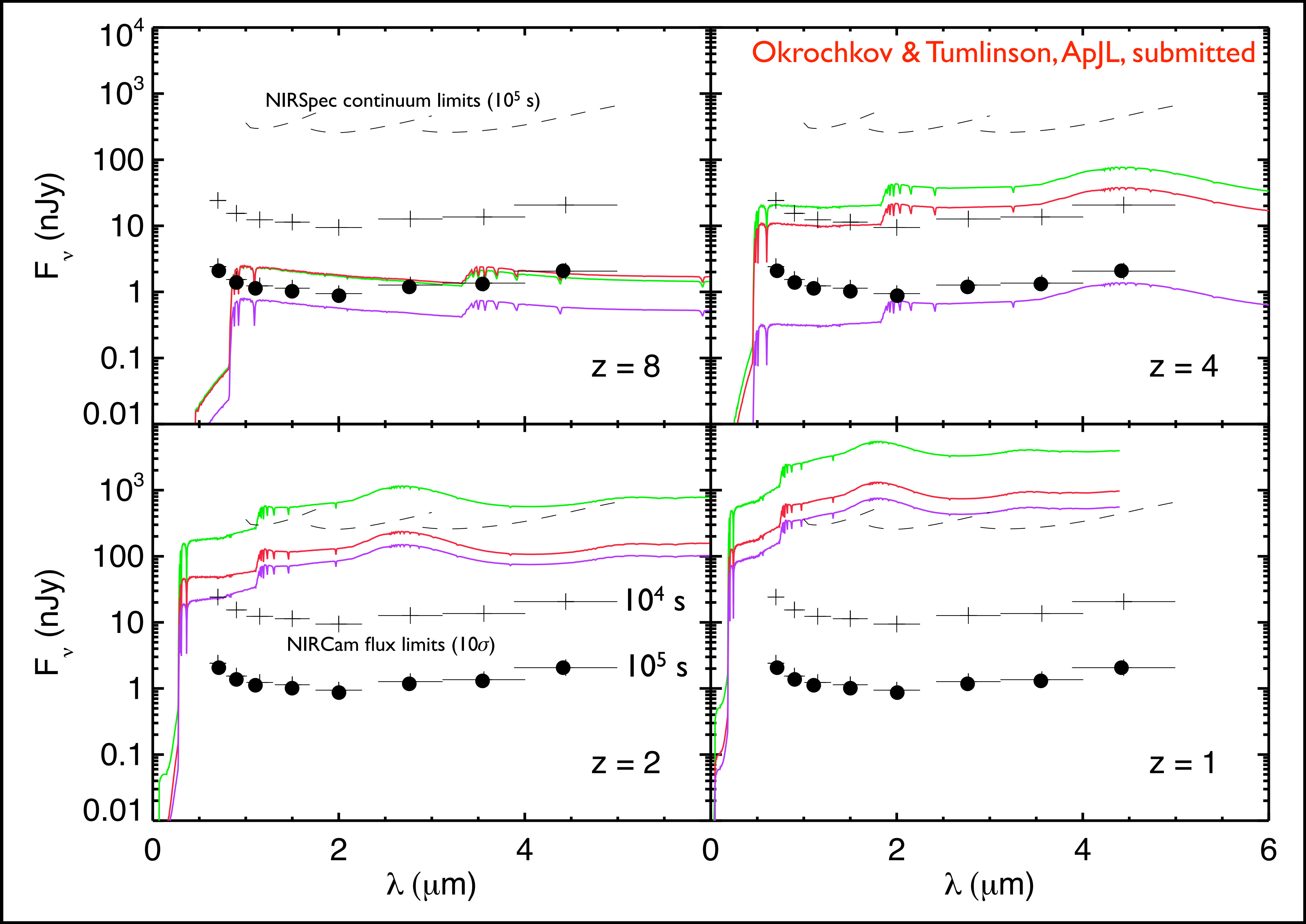
Simple prescriptions for baryonic physics:

1. Accrete baryons smoothly in fixed proportion to DM mass.
2. Form stars in discrete parcels in fixed, parametric proportion to gas mass.
3. Eject metals into the "ISM" by SN II, SN Ia, and AGB stars with appropriate time delay.
4. Allow selective ejection of metals and gas into "IGM", with more efficient ejection from small halos with shallow gravitational potential wells.
5. "Paint" stellar populations onto particles in proportion to their halo mass.

MW Halo Star Formation History

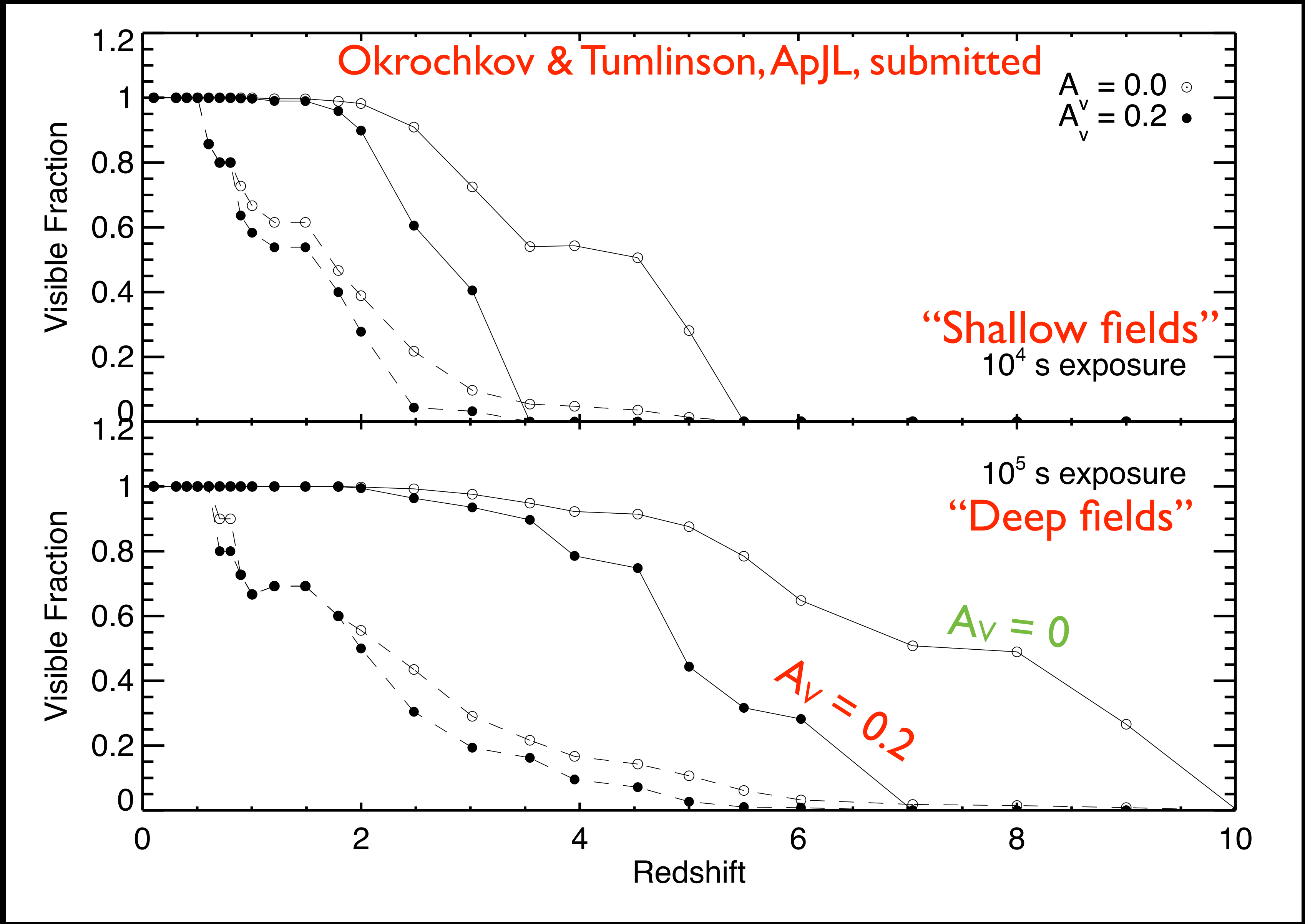


High Redshift Visibility of Milky Way progenitors



MW progenitors visible to z ~ 6 - 8 in JWST deep fields (~dust).

What fraction of the Milky Way's mass-in-place is visible to NIRCam?



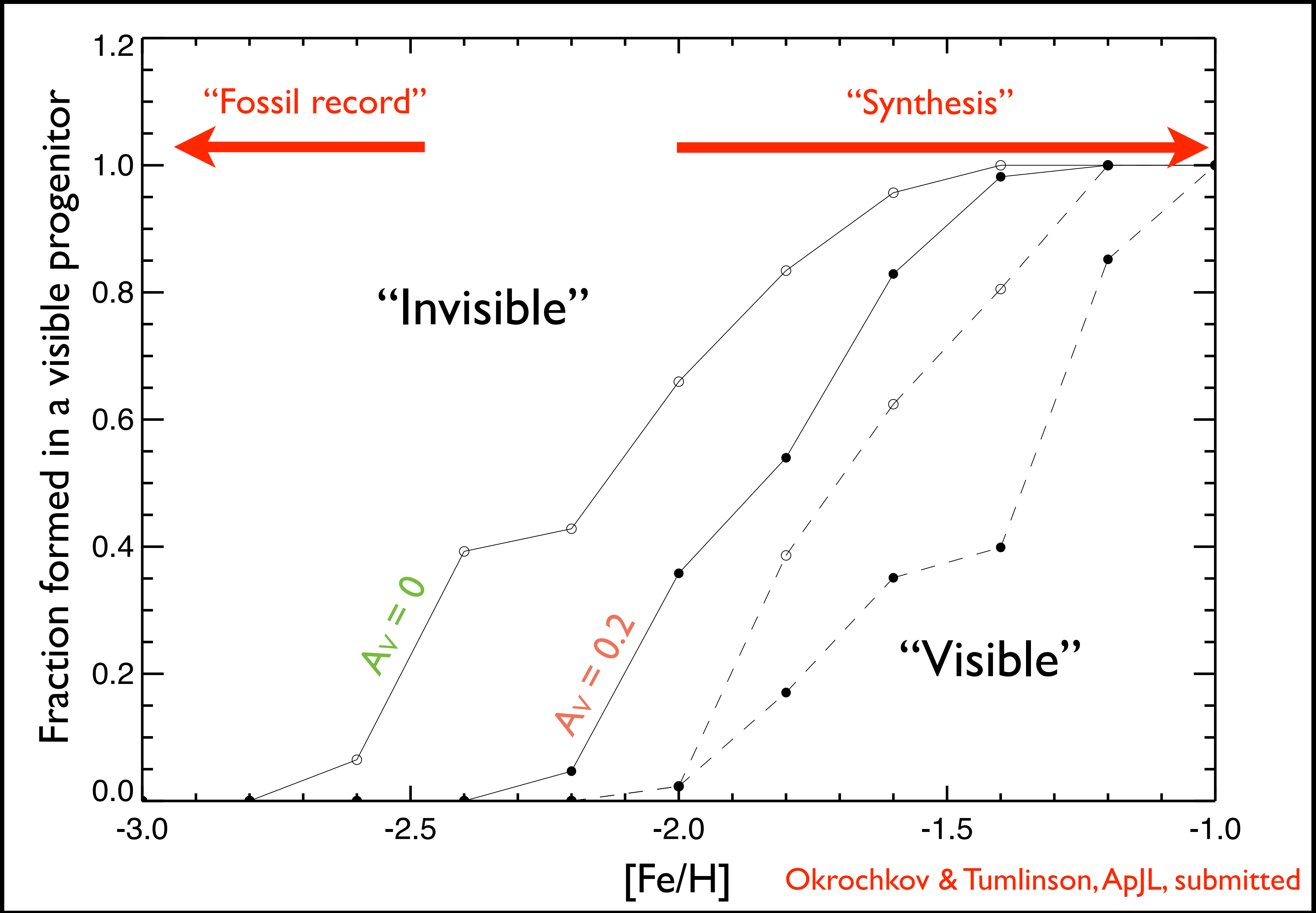
At z ~ 5, the visible MW progenitors account for roughly half the mass of the MW in place at that time (~dust).

Now: there are two kinds of stars that survive in the MW halo.

1) Those that formed in progenitors NIRCam can see.

2) Those that formed in progenitors NIRCam cannot see.

The High-Redshift Visibility of Galactic Metal-poor Populations



JWST will provide a lot of information on high-redshift galaxies. . .

but a large fraction of metal-poor stars in the Milky Way halo formed in galaxies that are invisible even in JWST / NIRCam deep fields! This is the ultimate reason to pursue "Galactic Archaeology" - to study galaxies we otherwise will not see!

First Big Challenge: Learn How to Synthesize

- Based on modeling of MW progenitors (Okrochkov & Tumlinson 2010):
  - [Fe/H] < -3 is the exclusive province of the "fossil record".
  - At [Fe/H] >~ -2, models testing "then and now" is possible .
- We need to learn how to:
  - Survey and identify galaxies at the right mass scale to be MW progenitor analogs.
  - Constrain star formation and chemical enrichment histories using "high-z" like indicators (SEDs, line indices) and "fossil record" indicators (chemical abundances, CMD-based SFHs).

Second Big Idea: The CMB-IMF

- Motivation (Richard Larson 2005):

  The CMB, T = 2.73 (1+z) K, sets a minimum floor for gas cooling, which should lead to a higher Jeans mass and higher characteristic stellar mass in the IMF:

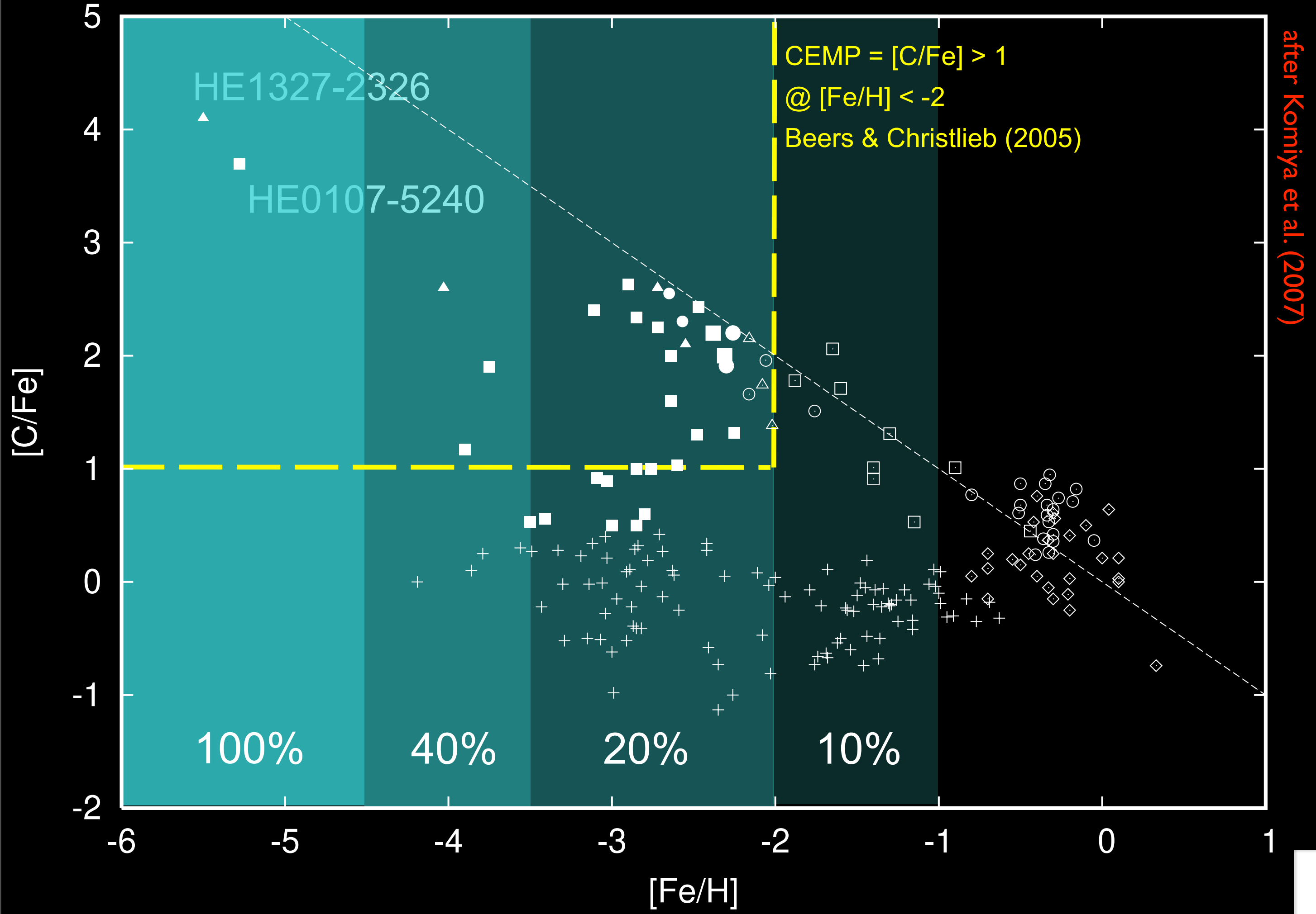
$$M_J \approx 0.9\ M_\odot\ [T_{CMB}/10K]^{1.70-3.35}$$

$$z = 5, 10, 20 \quad T_{CMB} = 16, 30, 57\ K \quad M_C = 2, 6, 17\ M_\odot$$

- If this is correct, the Pop III to Pop II transition will be mediated not just by metallicity, but also by redshift (equivalent to time).

- Important consequence: The effect is should be independent of metallicity! So IMF can be top-heavy at high *z* even in metal-rich galaxies (more to come from Britton Smith).

CEMPs and the CMB-mediated IMF?



At least 80% of CEMP stars are born as low-mass partner in a binary.

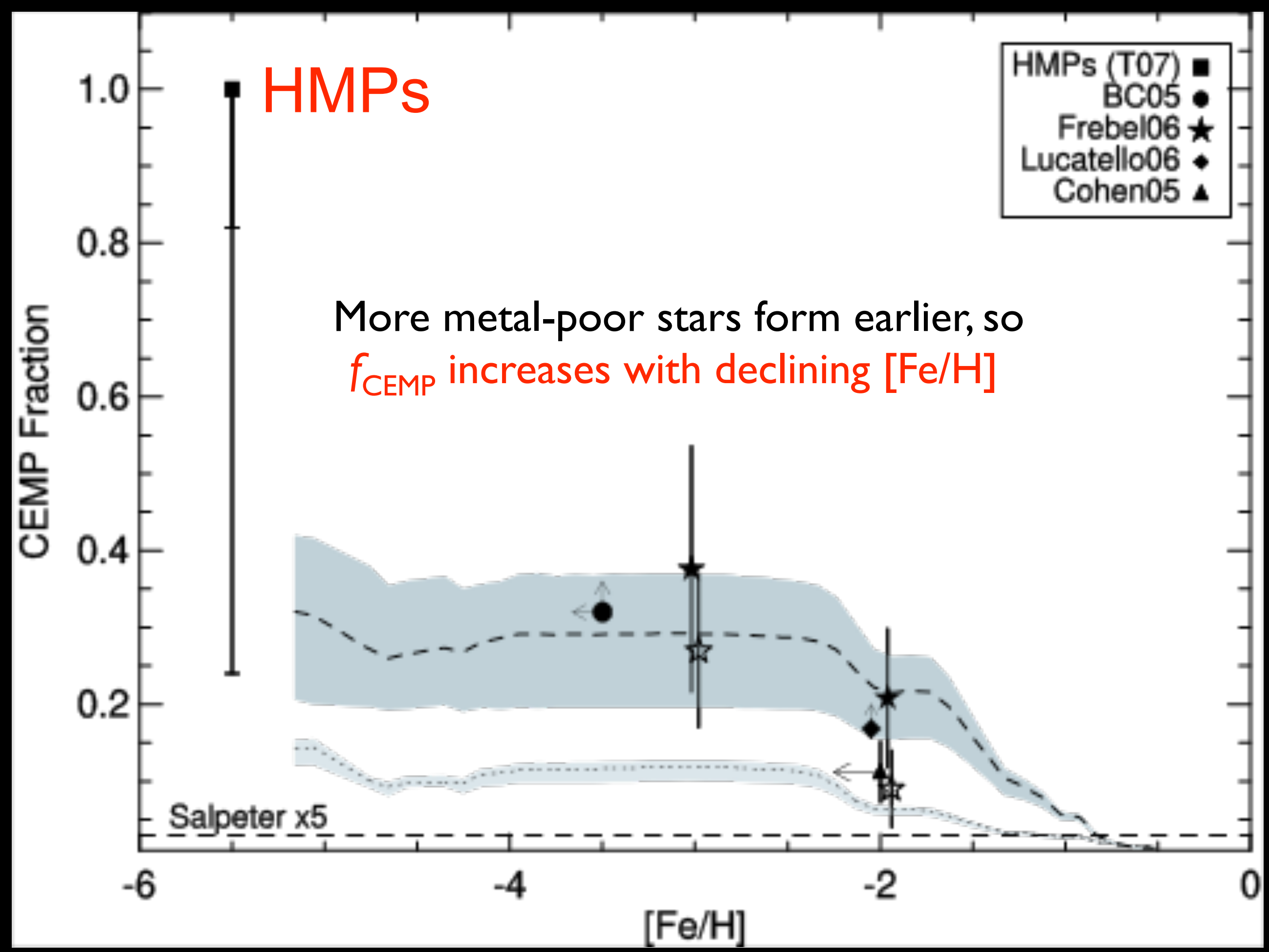
CEMPs are thus a sensitive probe of IMF in the range 1 - 8 $M_\odot$.

CEMPs also become more common in more metal-poor populations.

$$\ln\left(\frac{dN}{d\ln M}\right) = A - \frac{1}{2\langle\sigma\rangle^2}\left[\ln\left(\frac{m}{m_c}\right)\right]^2$$

The high fraction of CEMP stars in the halo, and its decline with increasing metallicity is consistent with a chemical evolution model in which the CMB sets the IMF.

(Tumlinson 2007, ApJ, 664, L63)



Tuesday, March 9, 2010

Second Big Challenge: Test the CMB-IMF

In the fossil record:

- Test for predicted gradient in CEMP fraction from older to younger stellar populations at the same metallicity.
- Look for other opportunities for relating redshift directly to IMF, such as in dwarf galaxies. *BUT . . . very hard to constrain redshift well for fossil record.*

At high redshift:

- Color / luminosity / stellar mass indicators (Davé 2008; van Dokkum 2008; Meurer et al. 2008).
- At the very least, determine whether a CMB IMF is consistent with the SEDs of observed high-redshift galaxies.

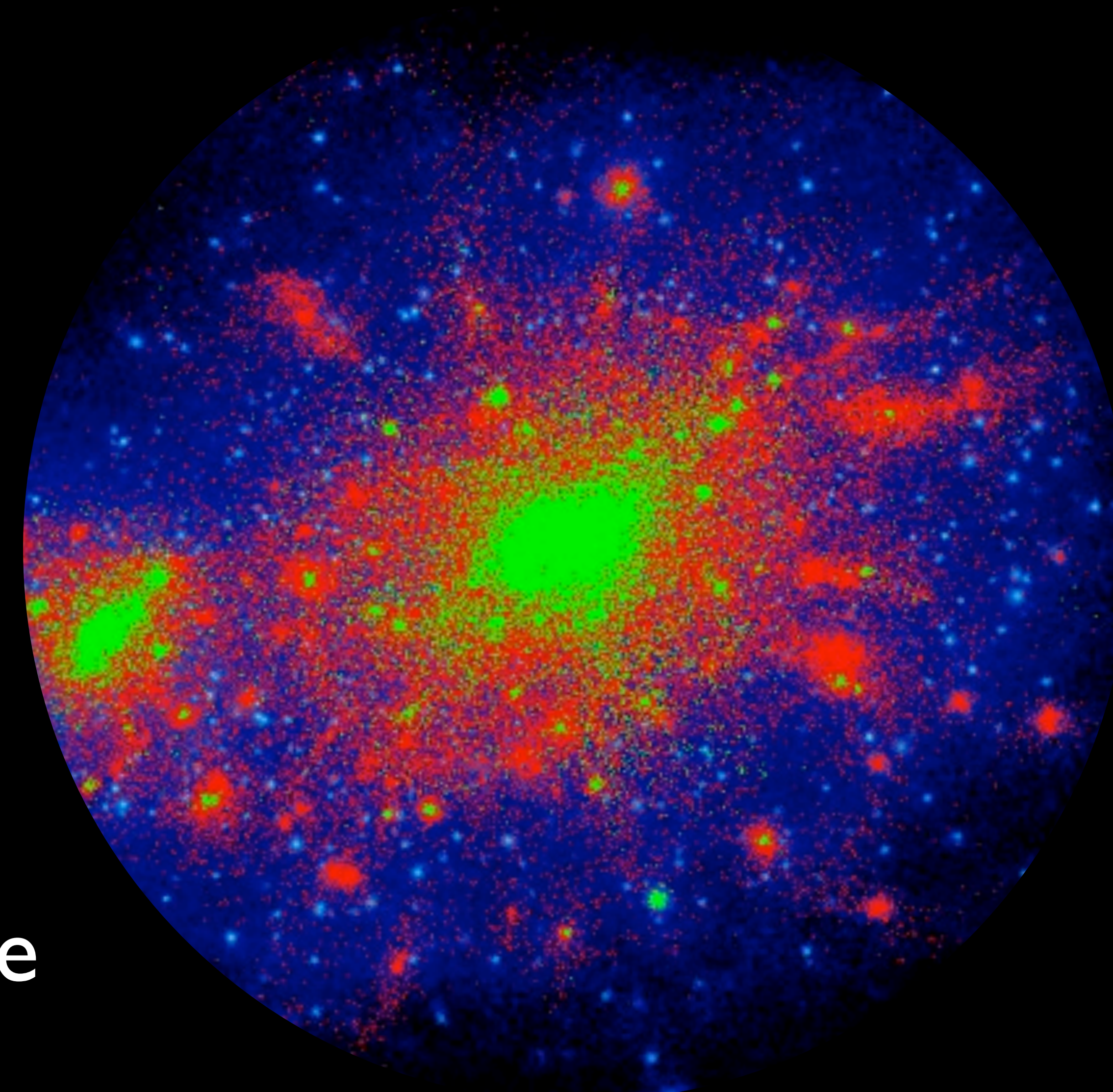
This is a perfect problem on which to build a synthesis of high and low redshift data.

Third Big Idea: Where to Look for the First Second Stars

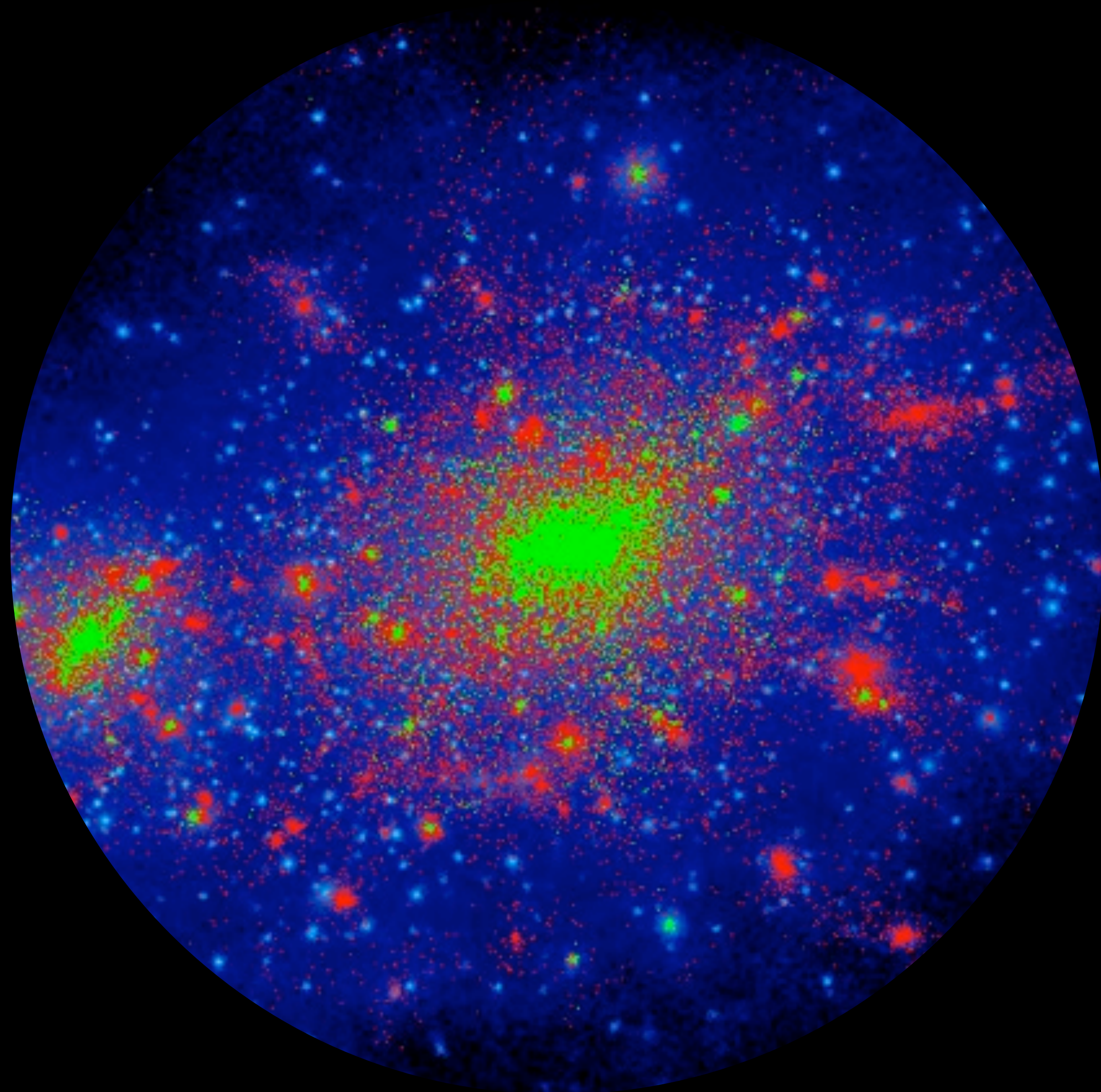
stars formed z > 10

stars formed at all z

[Fe/H] < -2.0

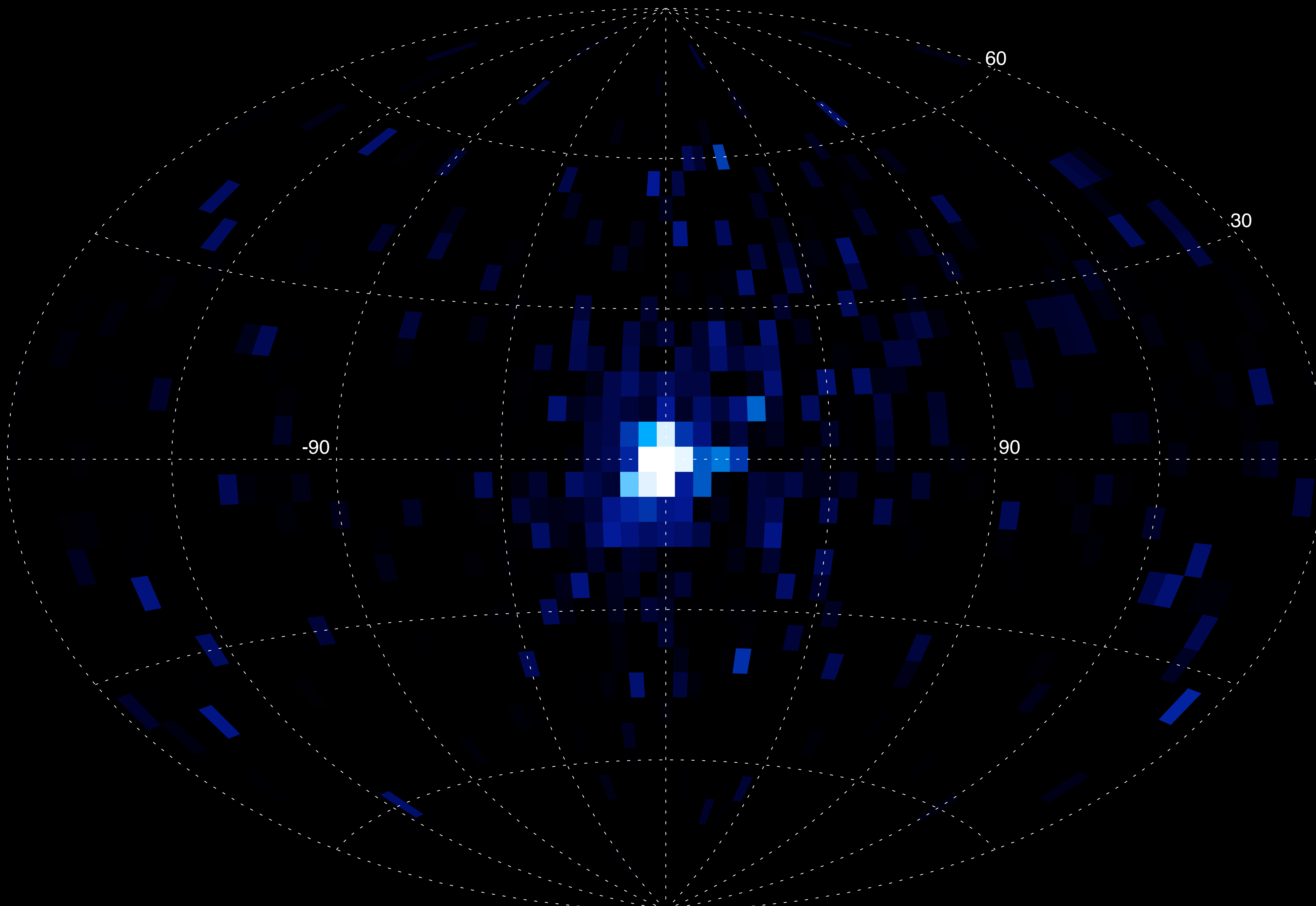


[Fe/H] < -3.5



Chronologically older stars are more centrally concentrated.

The Earliest Halos Deposit Stars in the MW Center



Pop III survivors are "in the bulge", but not "of the bulge"…

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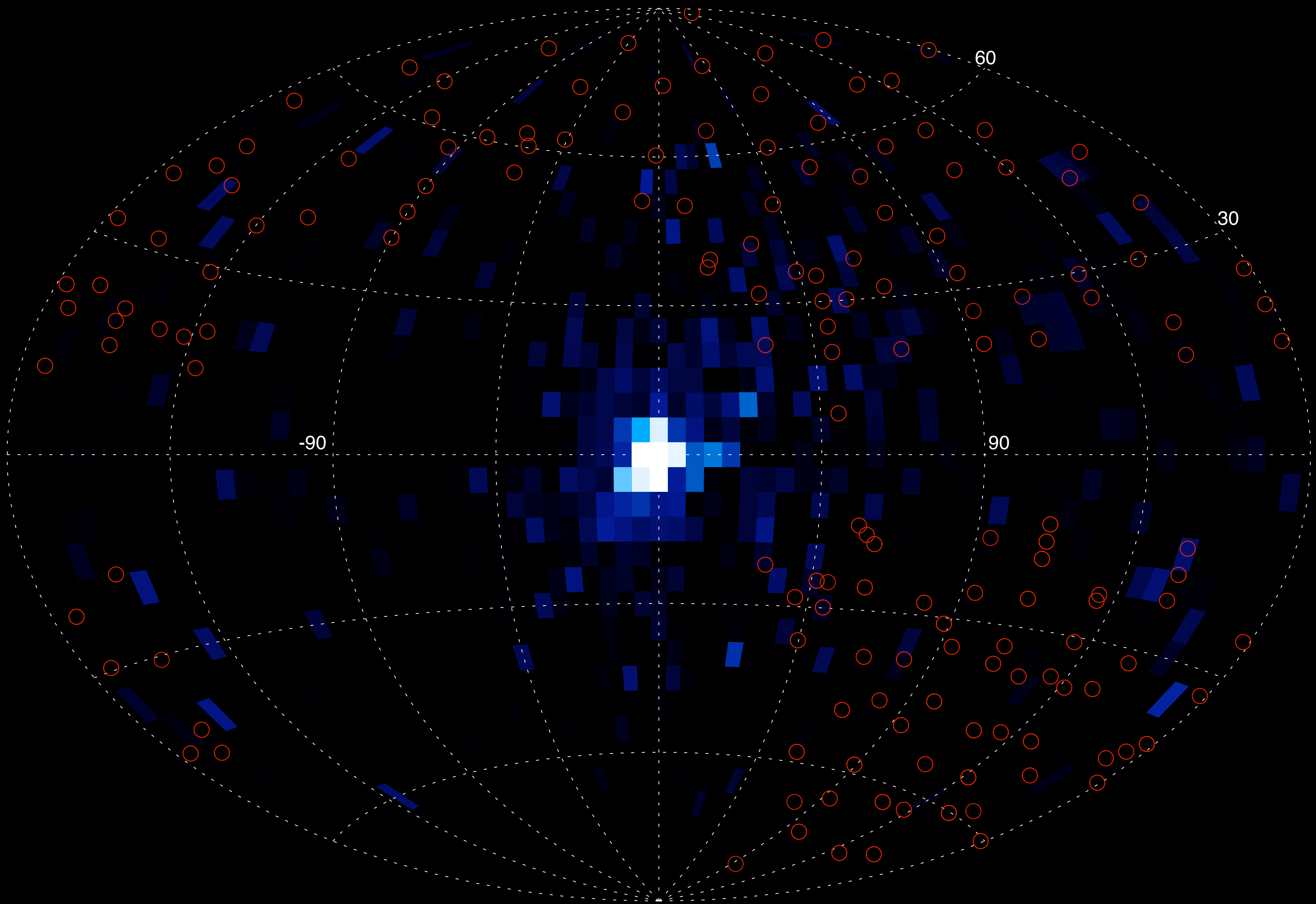
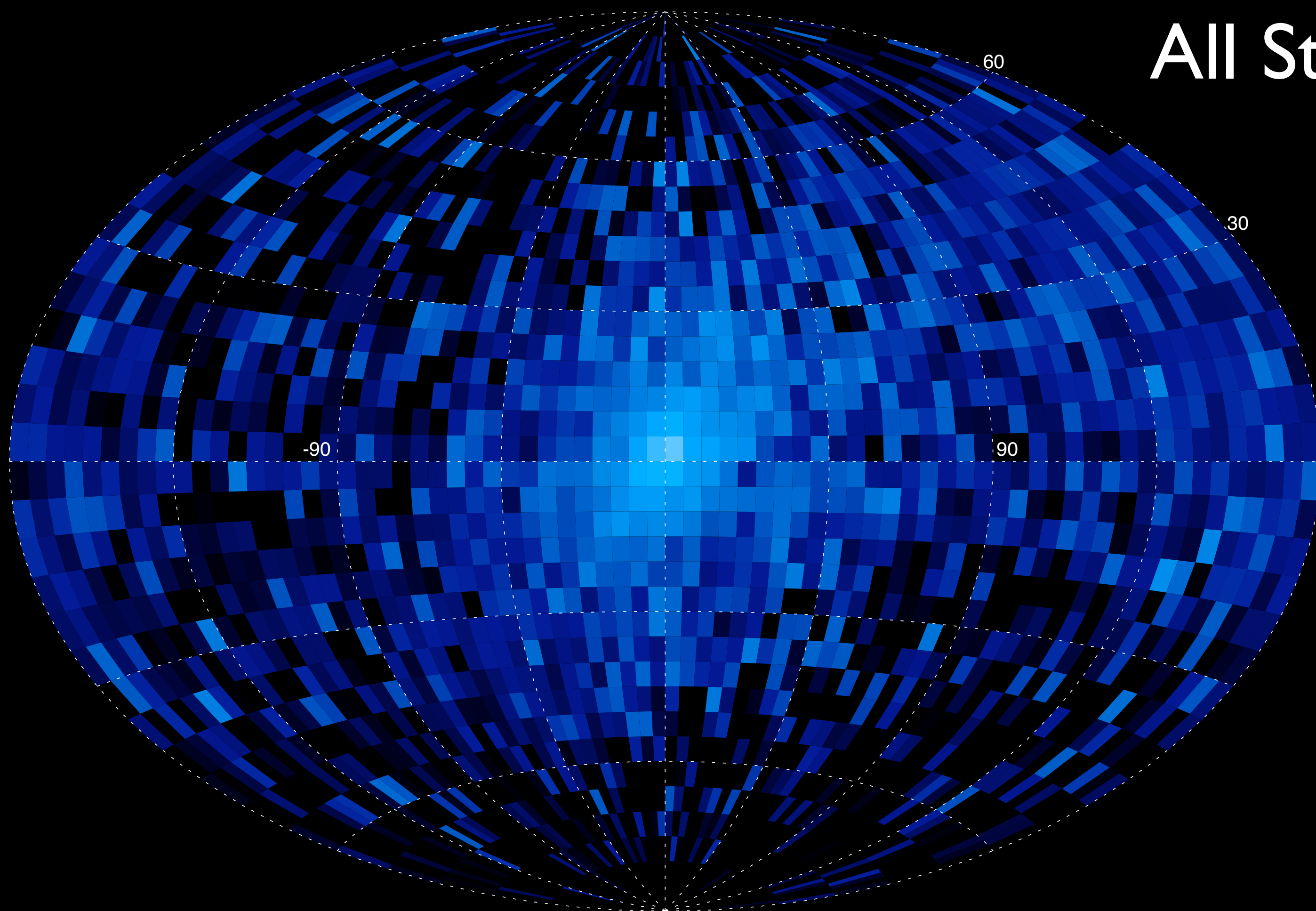
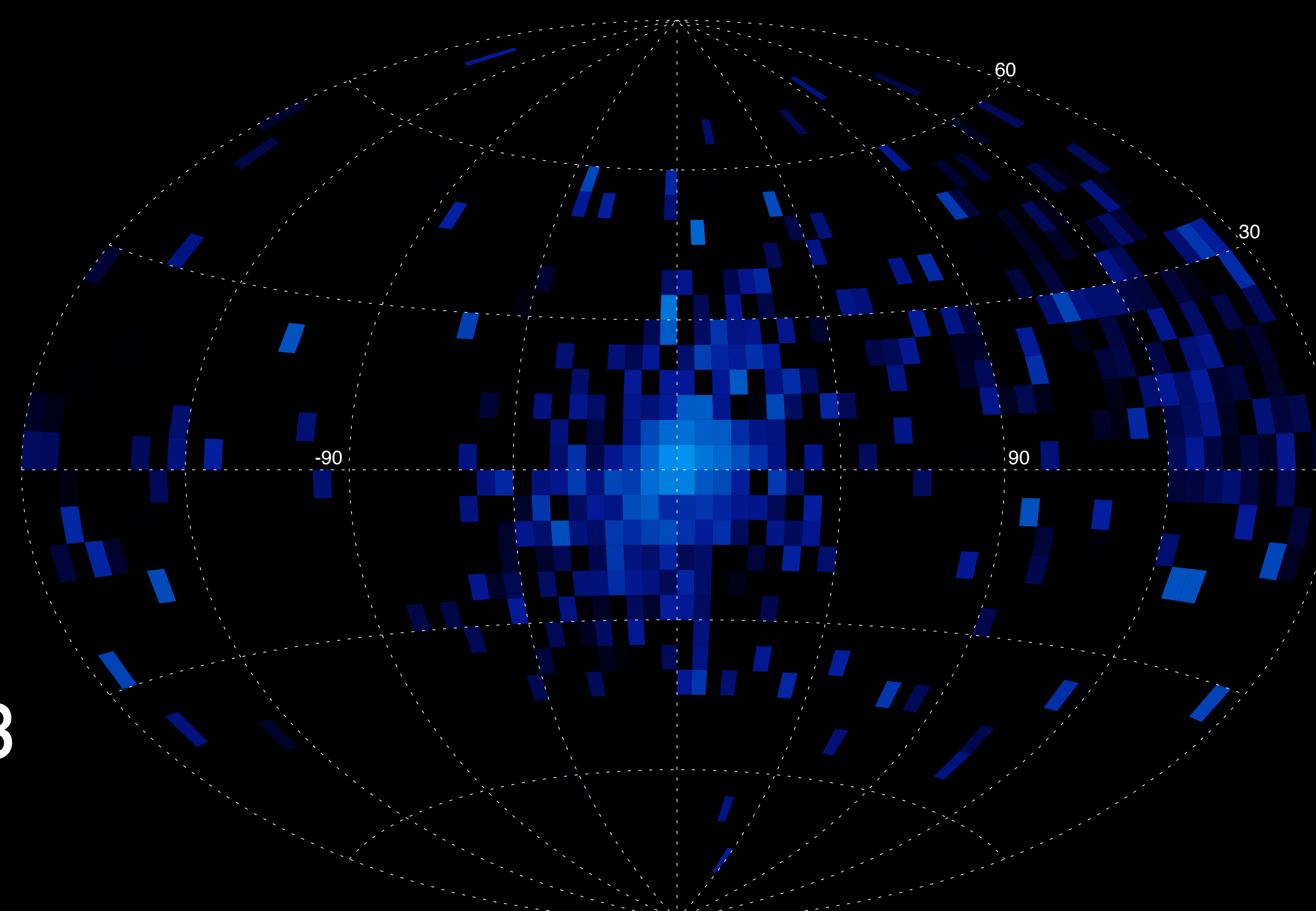


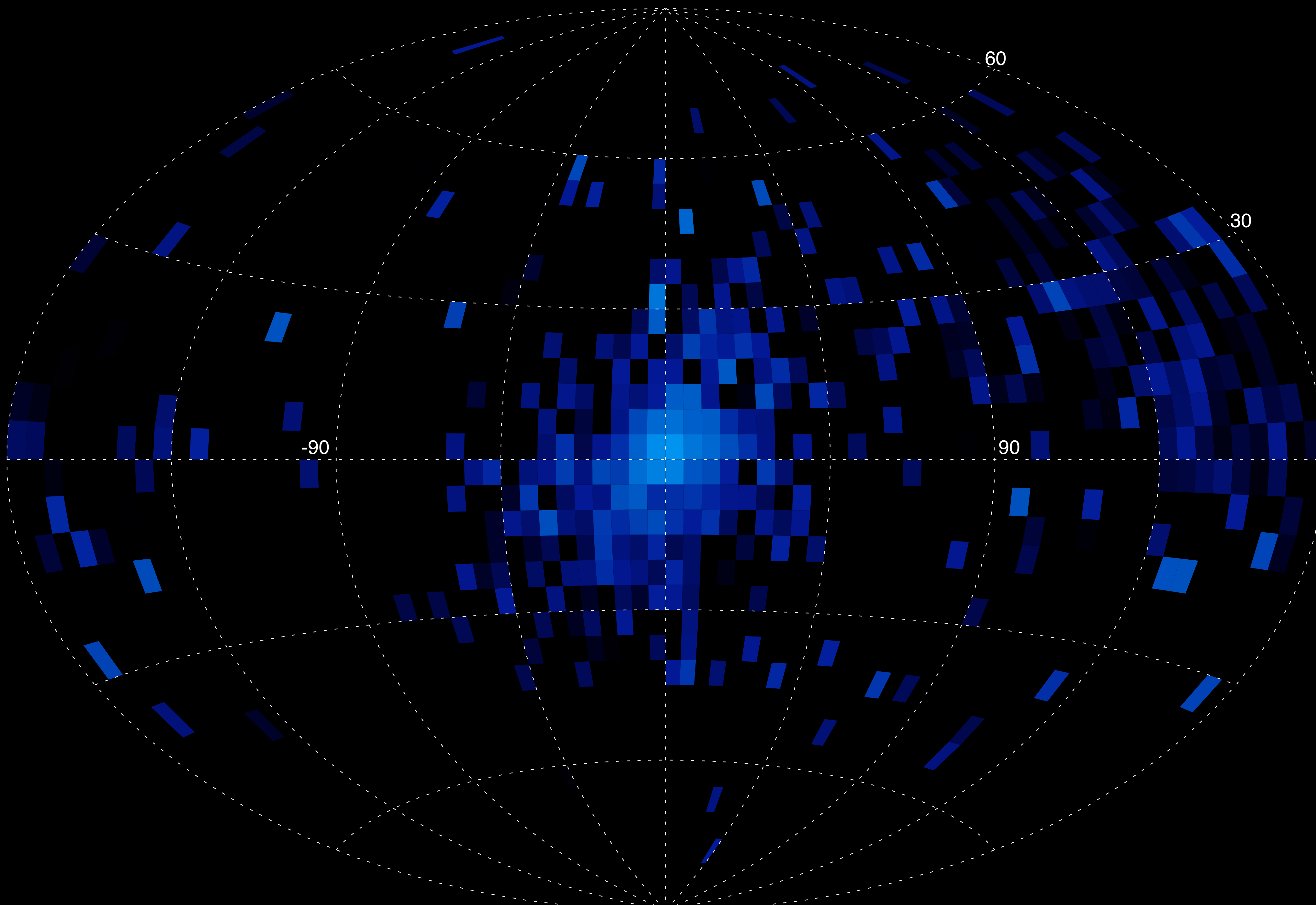
Pop III survivors are "in the bulge", but not "of the bulge"…



All Stars with [Fe/H] < -3



All Stars with [Fe/H] < -3
from z > 15


60
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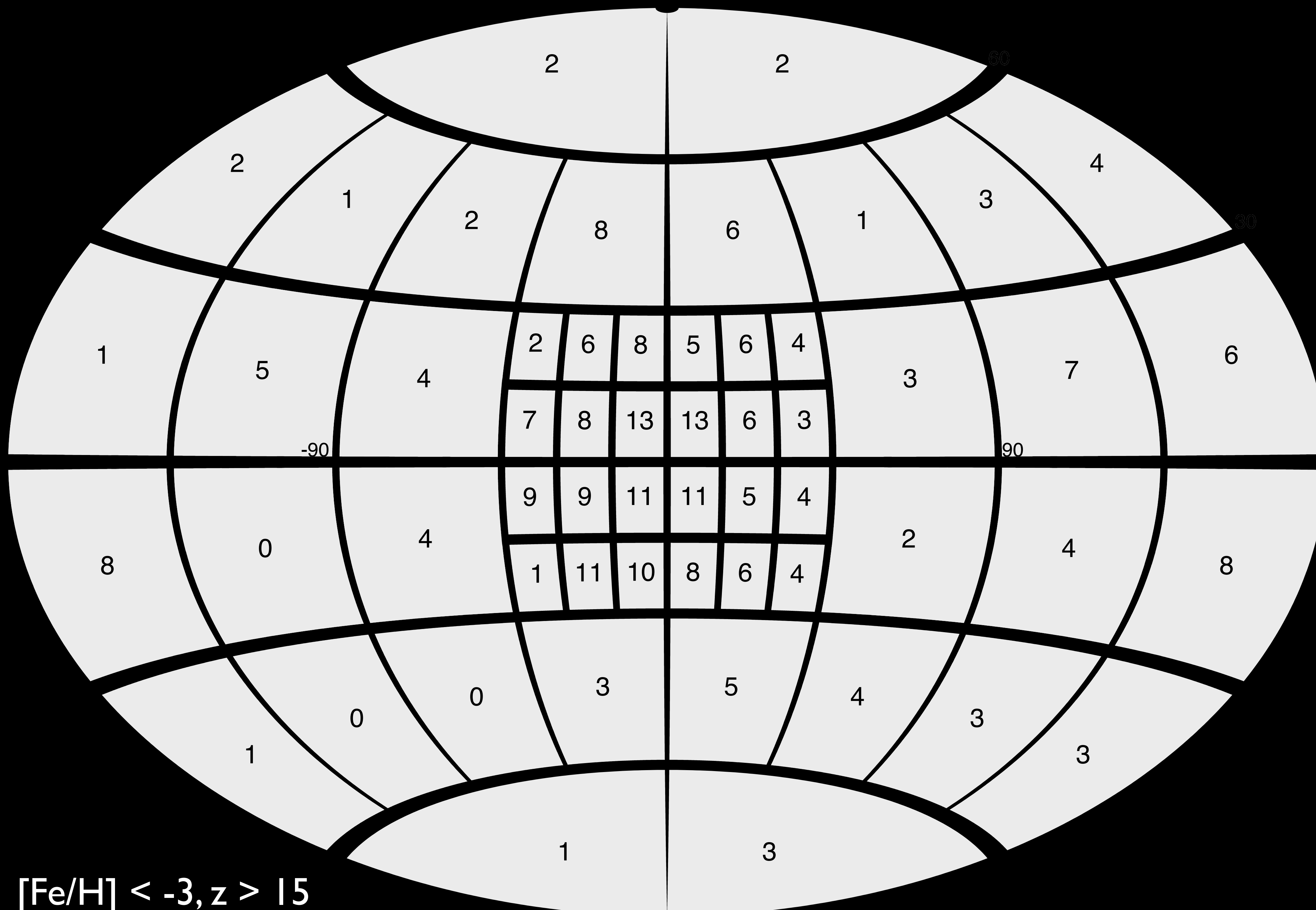
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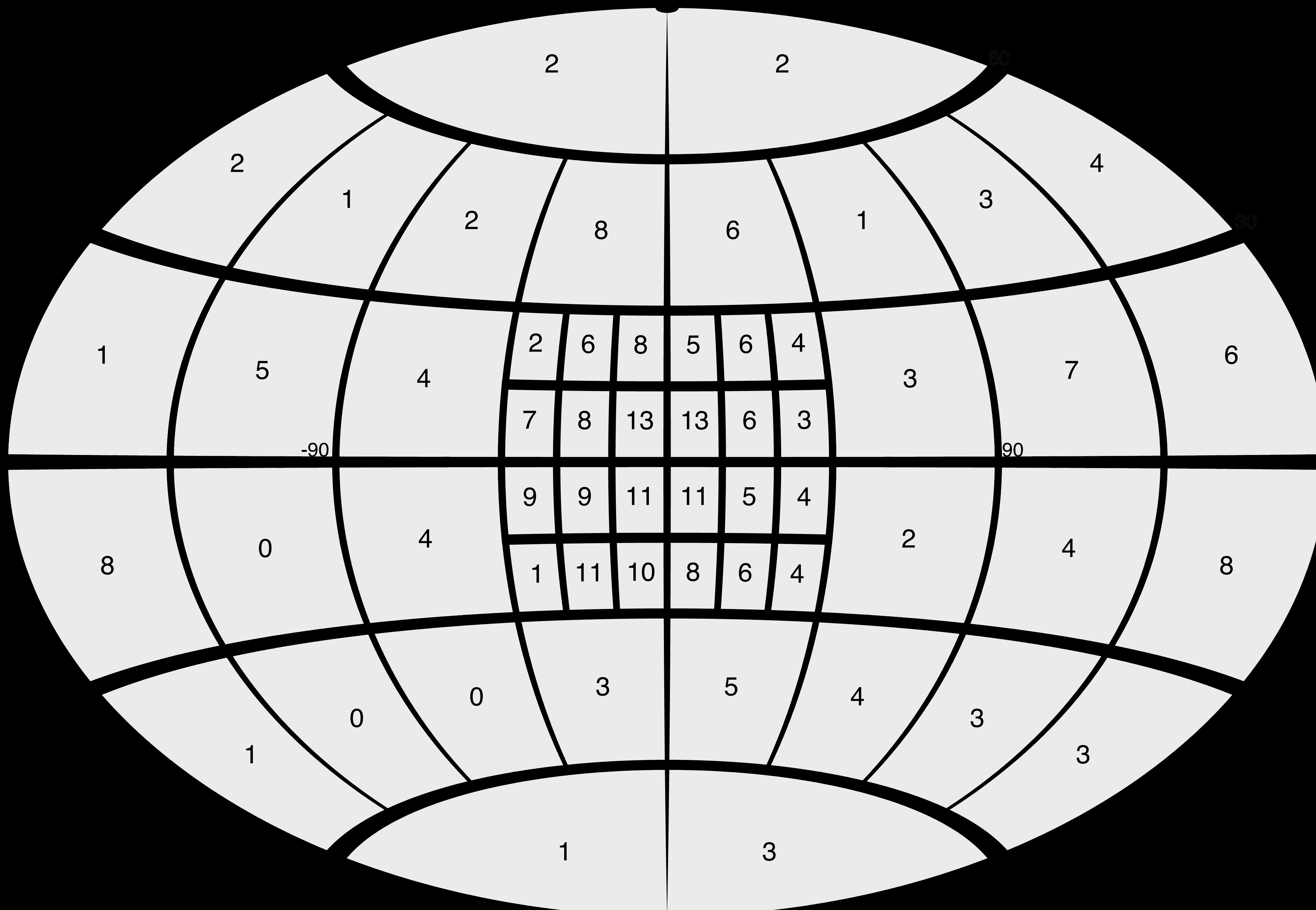
30
1 5 4 2 6 8 5 6 4 3 7 6
7 8 13 13 6 3
-90
90
9 9 11 11 5 4
2 4
8 0 4 1 11 10 8 6 4 8
3 5
0 0 4 3
1 3
1 3

[Fe/H] < -3, z > 15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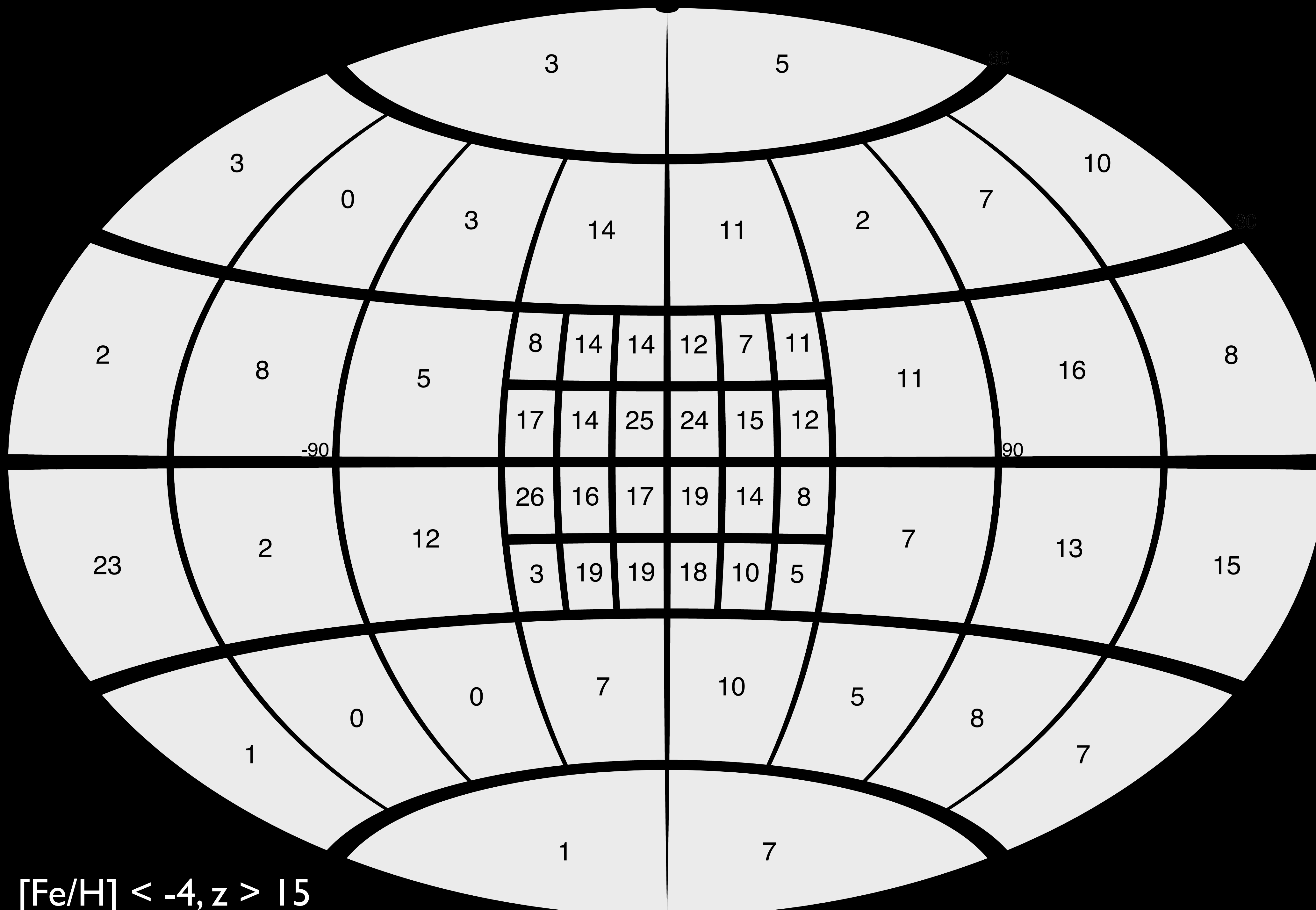
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23 2 12 3 19 19 18 10 5 7 13 15
1 0 0 7 10 5 8 7
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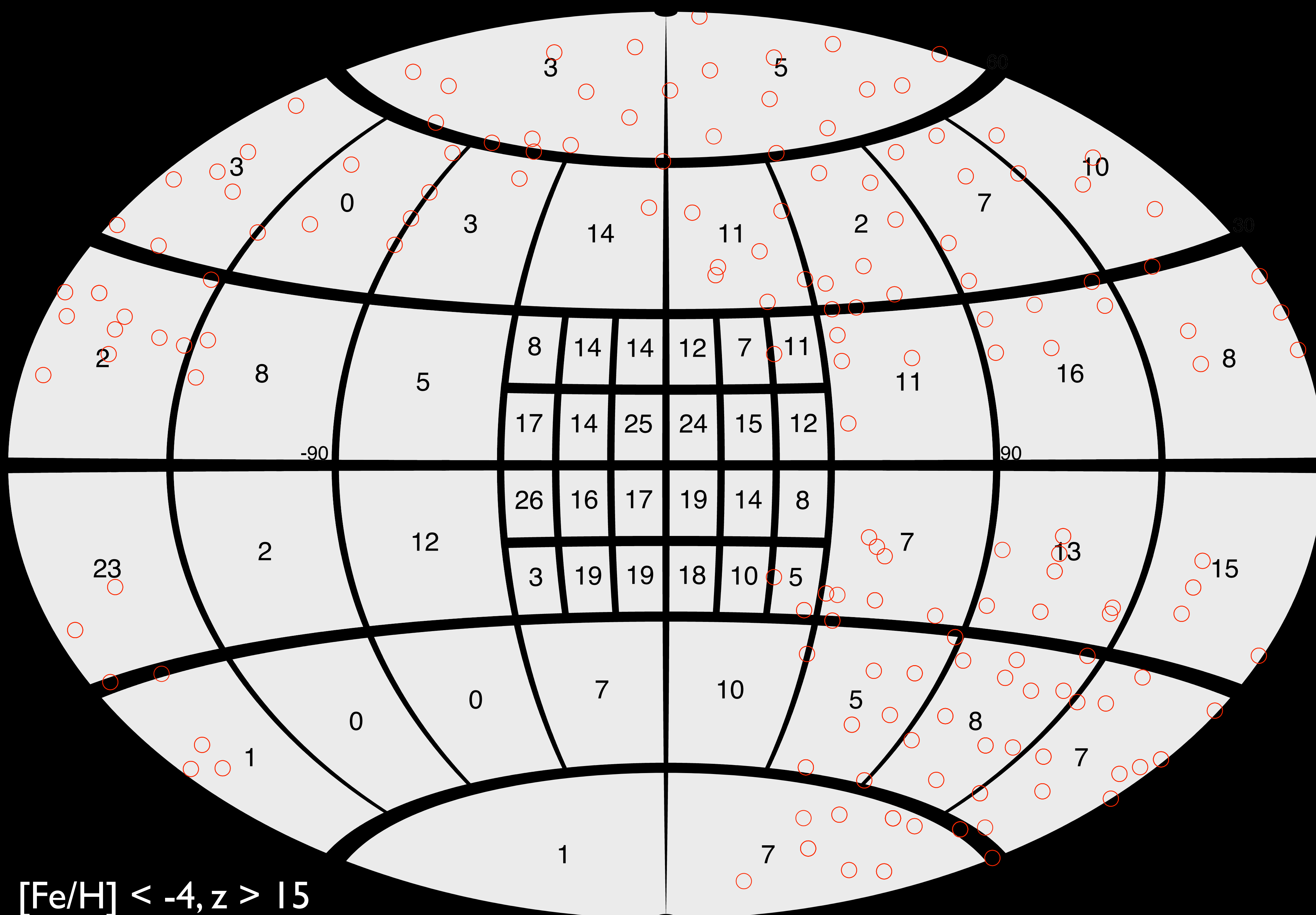
[Fe/H] < -4, z > 15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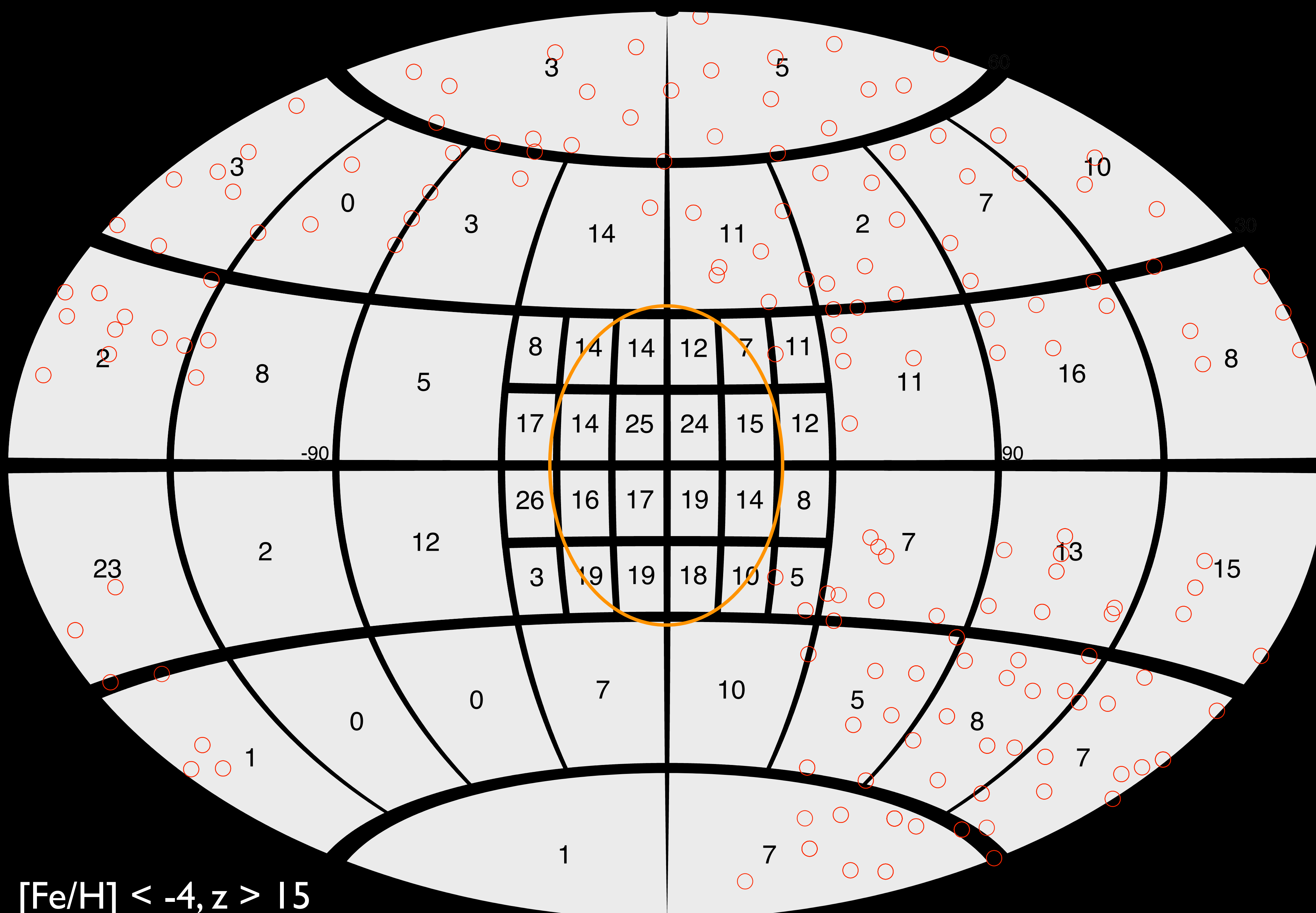
[Fe/H] < -4, z > 15



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17 14 25 24 15 12
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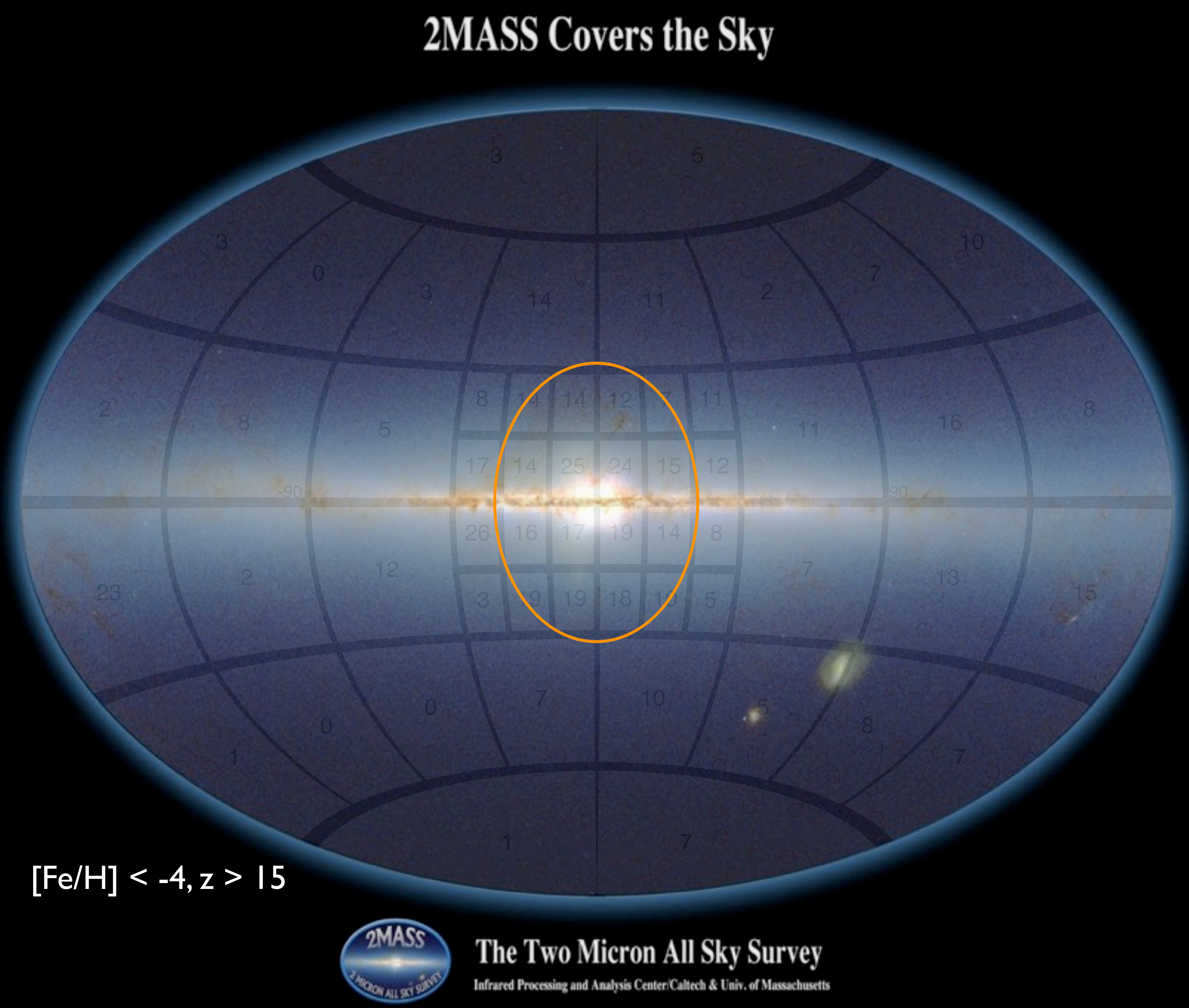
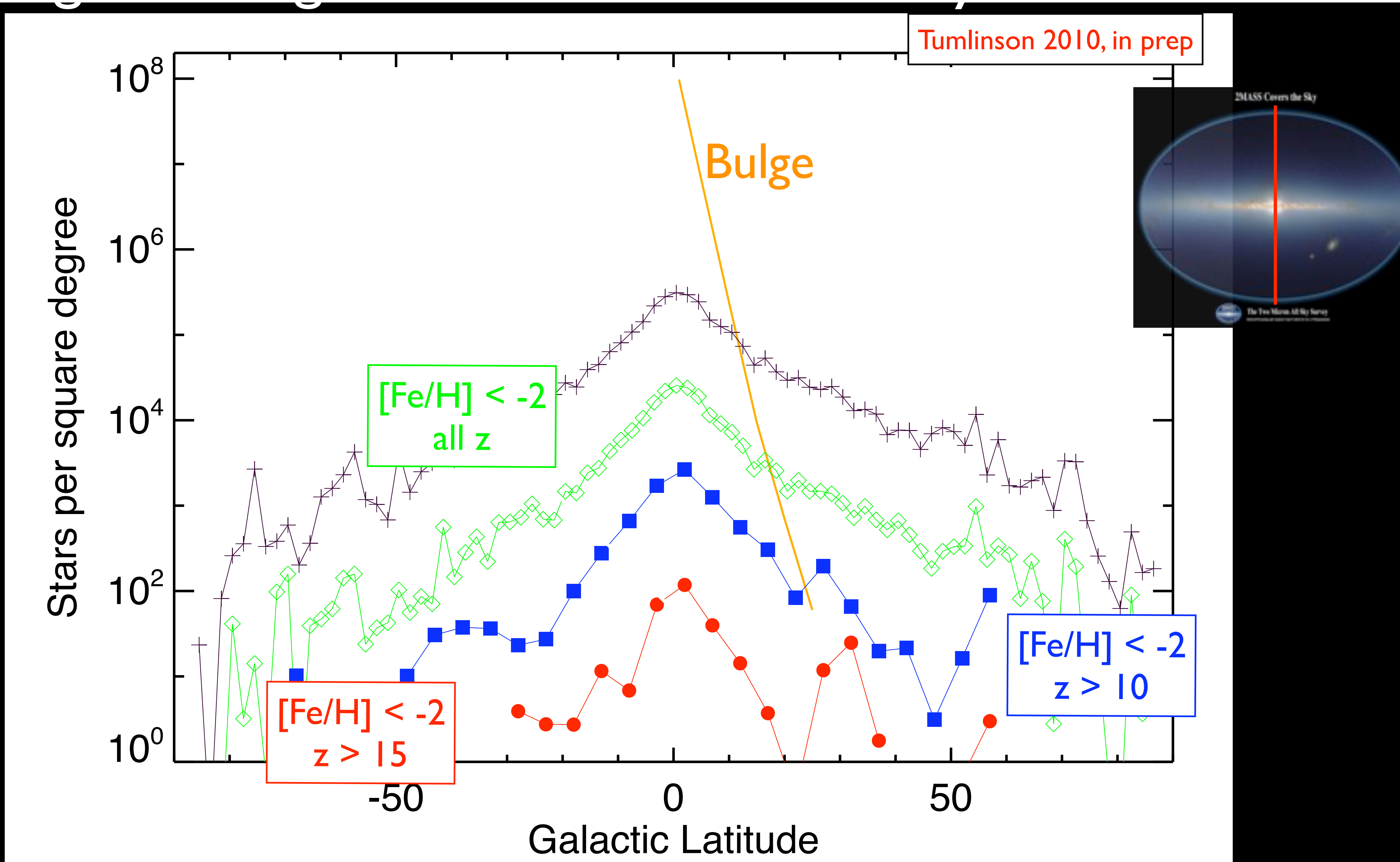
1 7

[Fe/H] < -4, z > 15


2MASS Covers the Sky
2MASS
The Two Micron All Sky Survey
Infrared Processing and Analysis Center/Caltech & Univ. of Massachusetts

[Fe/H] < -4, z > 15

Third Big Challenge: Probe the Inner Galaxy for "Second Stars"



Key issue: Halo stars reside at all places on the sky (black curve), but very ancient VMP stars, z > 10, prefer < 20° from GC (blue curve) and z > 15 barely exist outside > 10° from the center (red curve).

In these regions, there are 100 - 1000 VMP stars per square degree from z > 10.

So: how can we find and study metal-poor stars in such crowded places?

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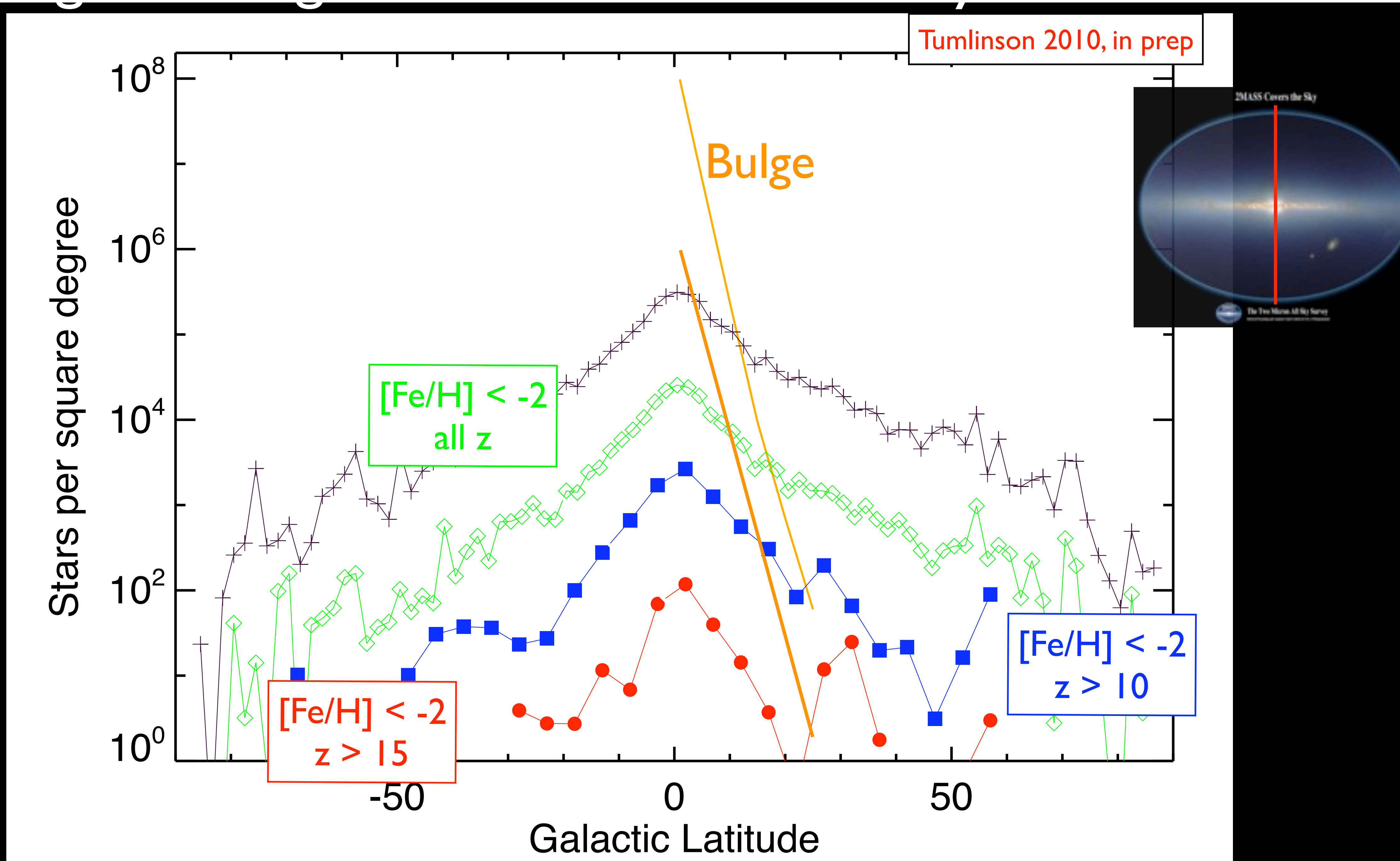

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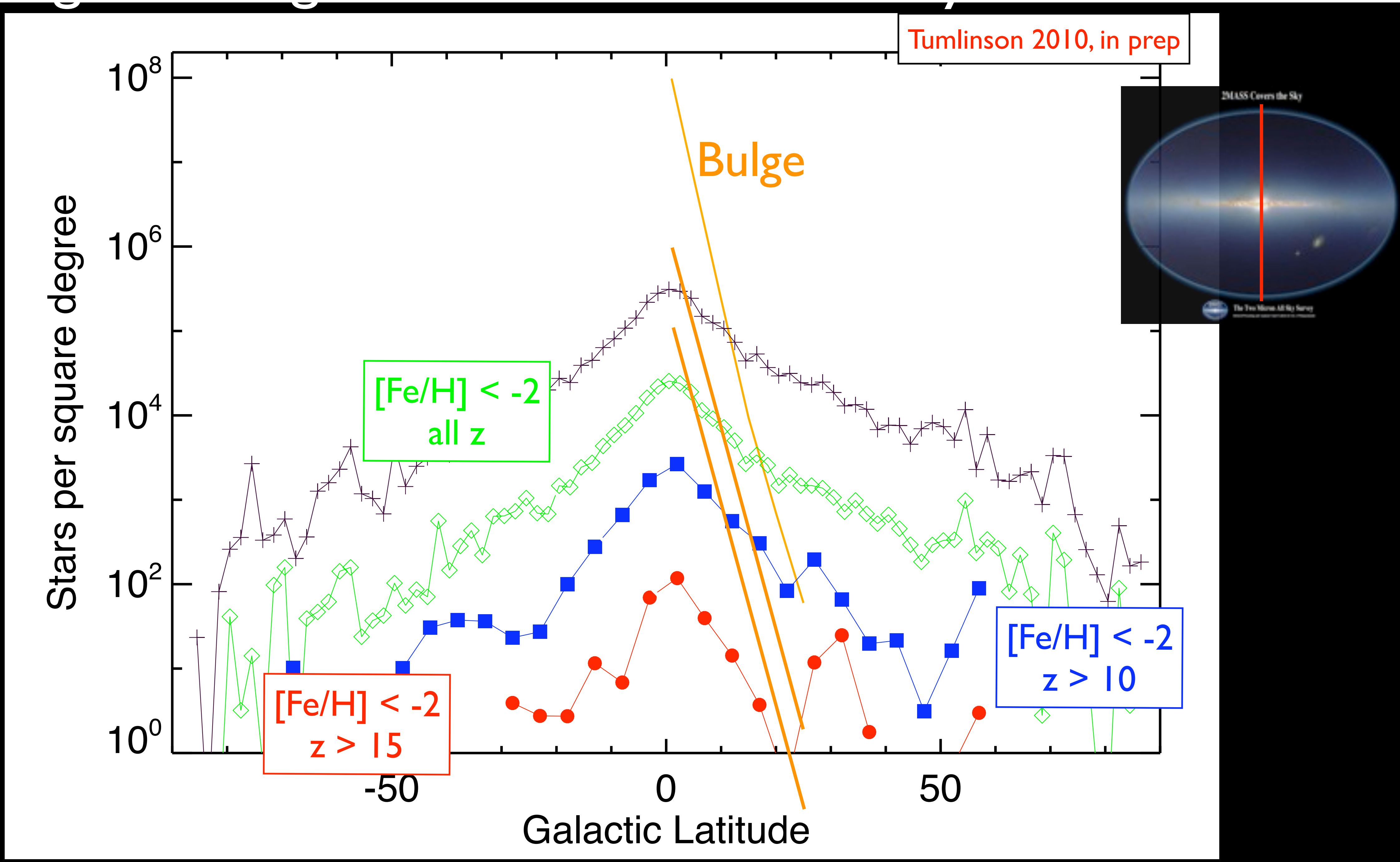

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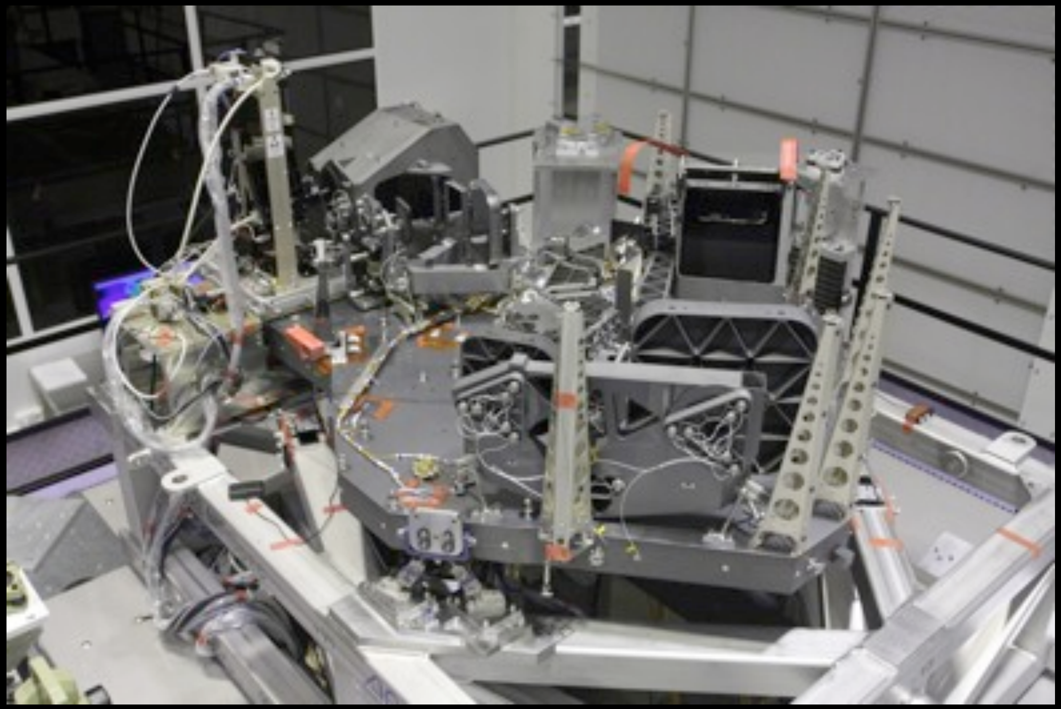
JWST/NIRSpec to the Rescue?



JWST / Near-Infrared Spectrograph

- ESA-contributed facility instrument (led by Peter Jakobsen)
- MOS capability enabled by 250,000 shutters over a 3.5x3.5 arcmin field
- R = 100, 1000, 3000 from 1 - 5 μm.

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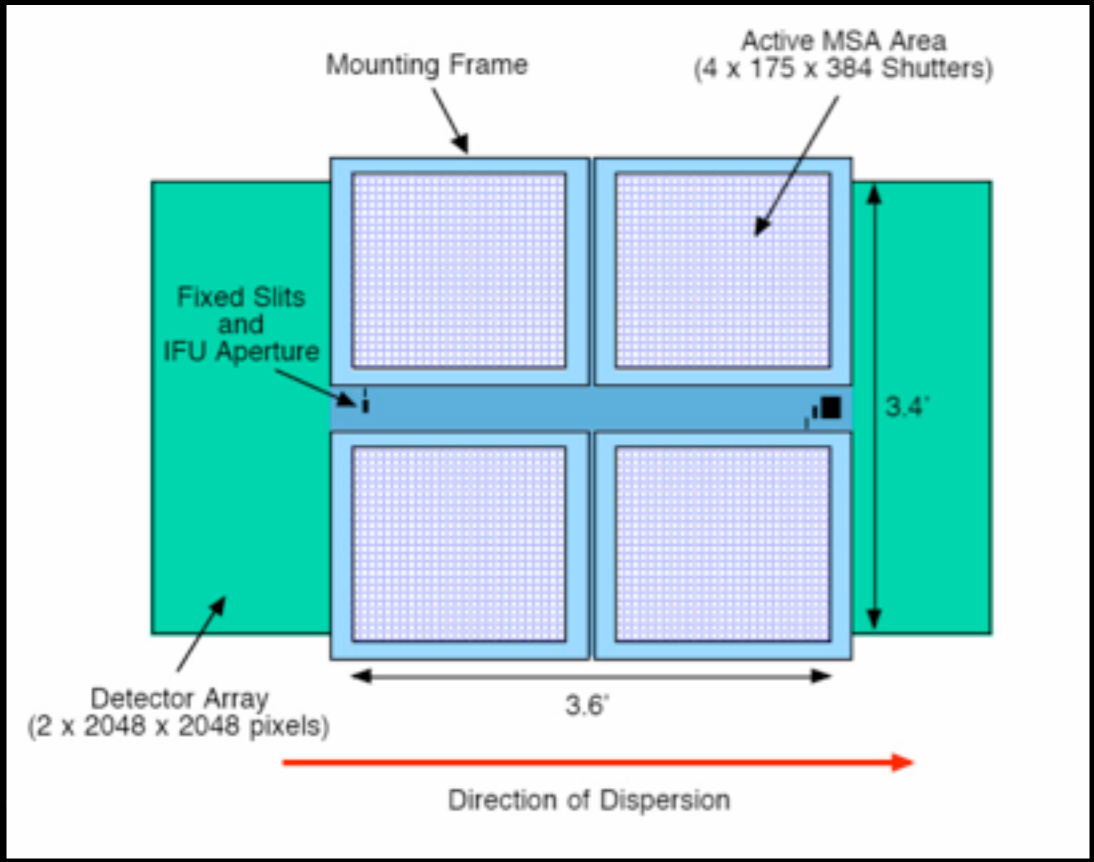

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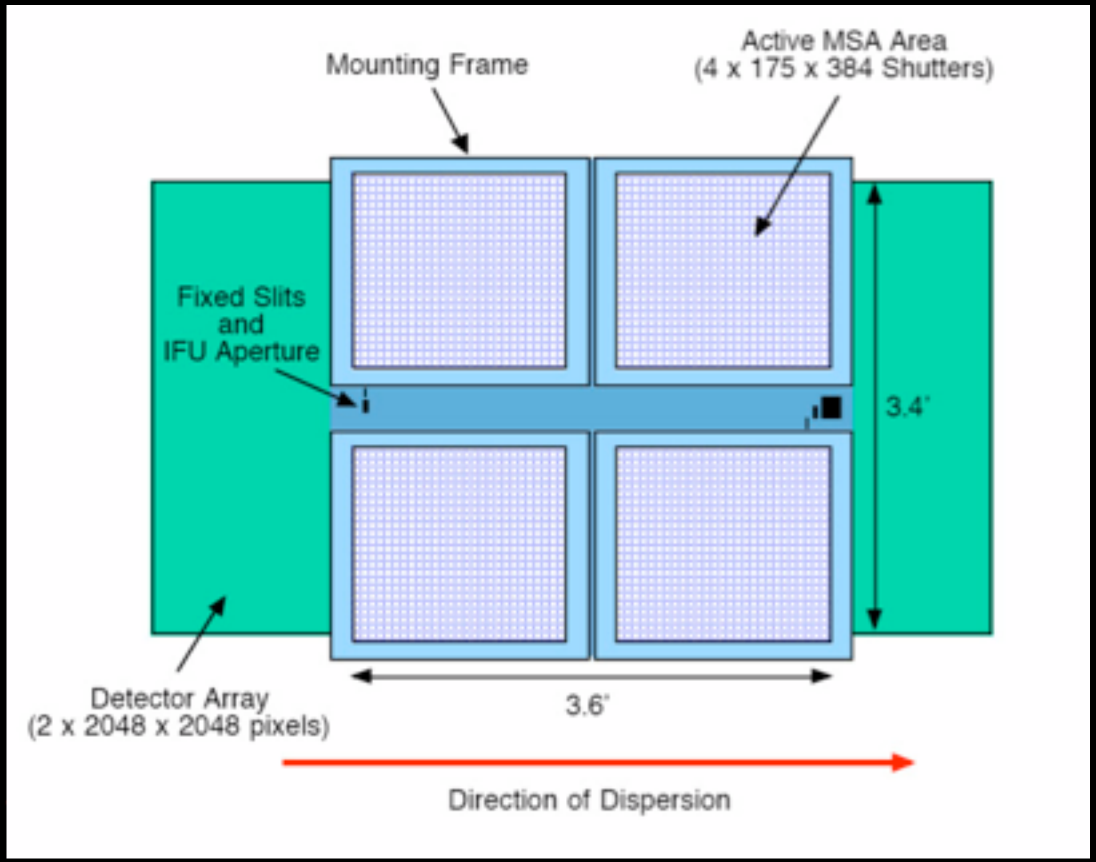

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- R = 100, 1000, 3000 from 1 - 5 μm.

The challenge: can NIRSpec read the fossil record in the inner galaxy and bulge?

- at 8 kpc, the MSTO lies at K = 17.4 (unreddened), with up to 10^7 stars per square degree or 300 per FOV with 99% photometric pre-selection.
- NIRSpec will obtain S/N = 100 in ~15 minutes at this magnitude, ~ 100 objects at a time over a 3.5 x 3.5 arcmin field.
- How to pre-select for metal-poor stars, throwing out bulge stars at 1000:1?

Three Big Ideas, Three Challenges

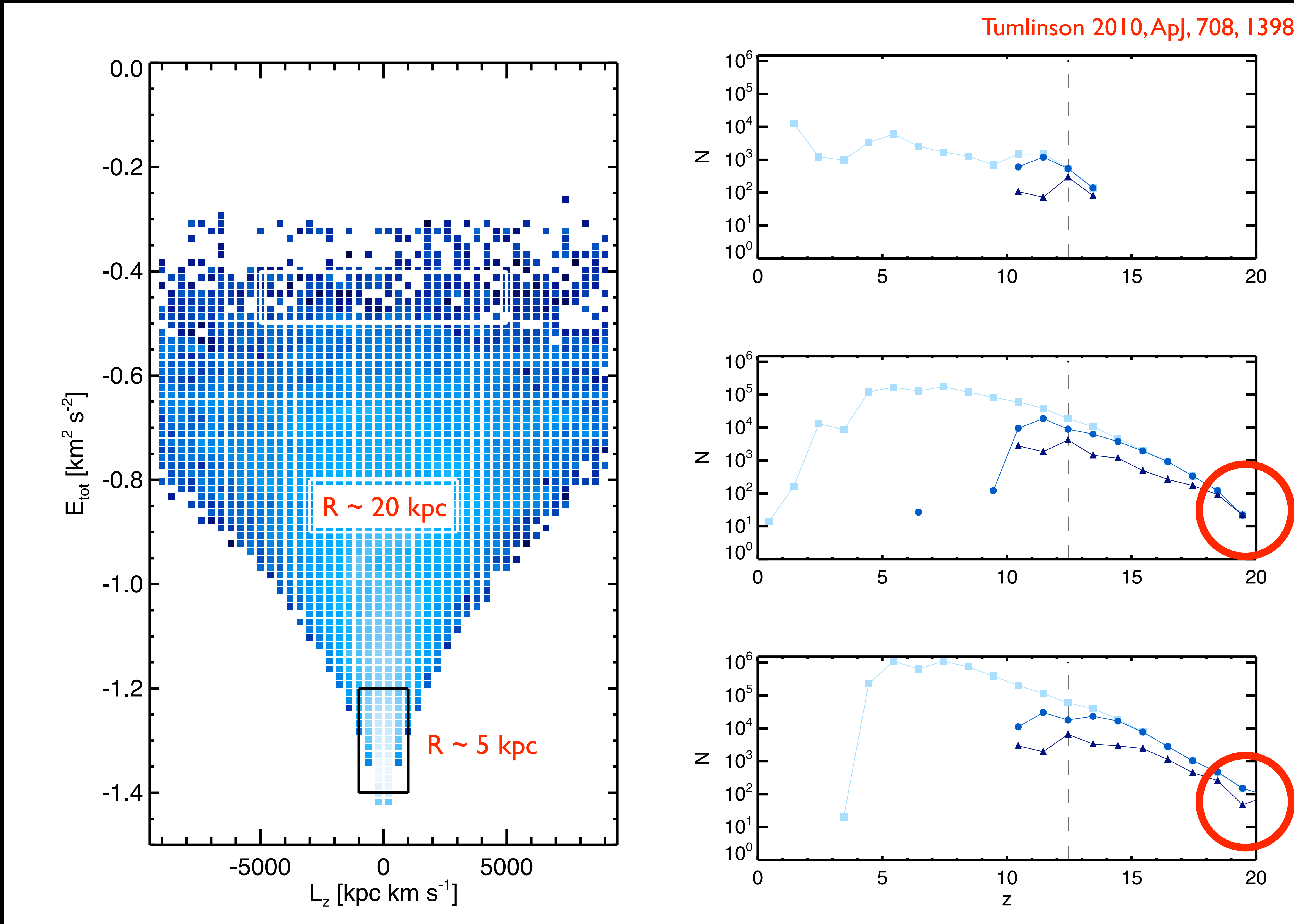
1. To study the first stars and the Pop III to Pop II transition, we must learn how to study the evidence of the fossil record.

2. To test the CMB-IMF, we must learn how to synthesize this fossil evidence with observations from high redshift.

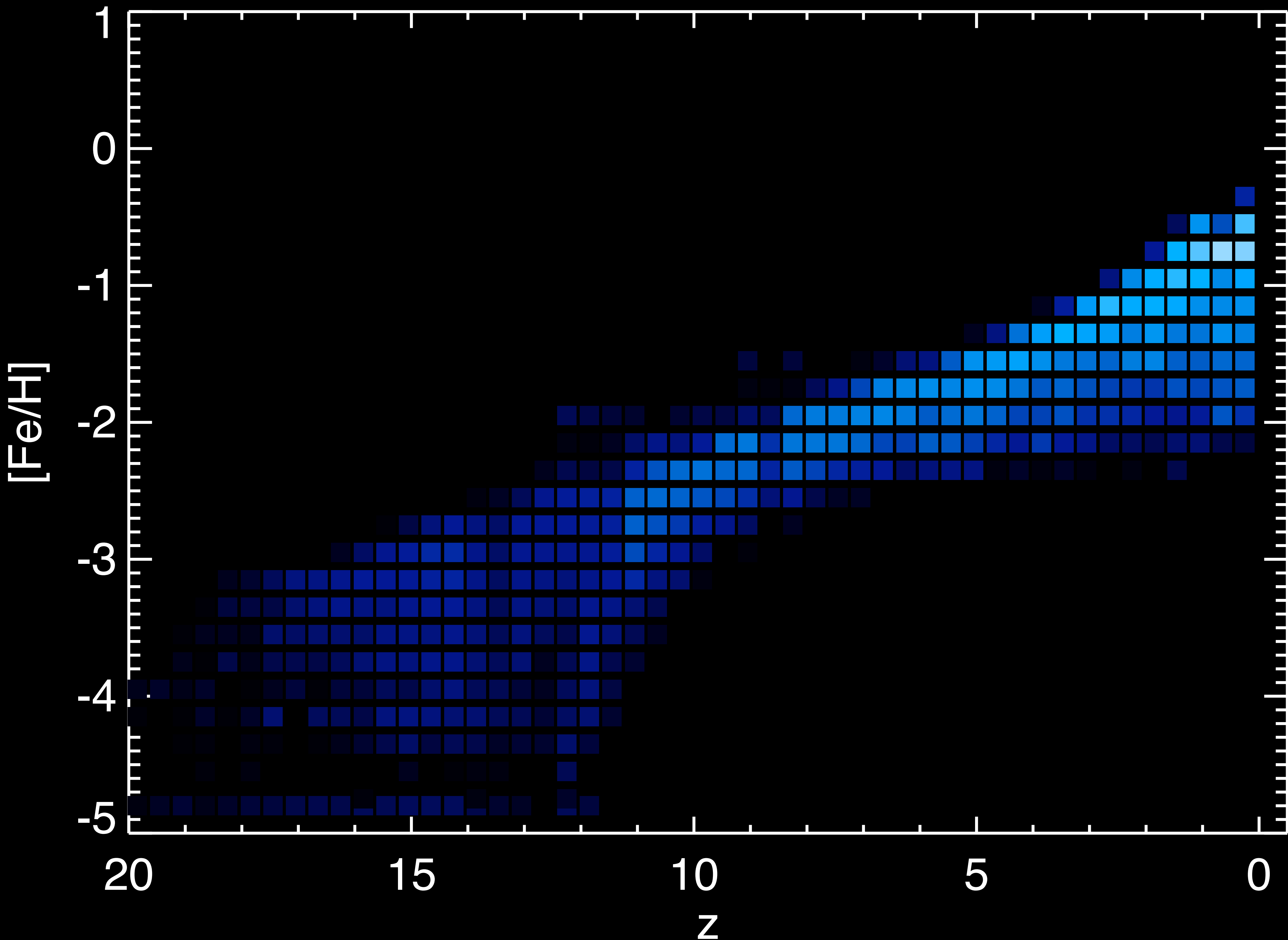
3. To find the earliest residues of the first stars, we must examine the metal-poor stars in the innermost Galactic halo (and try JWST!).

END

Third Big Idea: Where to Look for the First Second Stars



MW Halo Star Formation History



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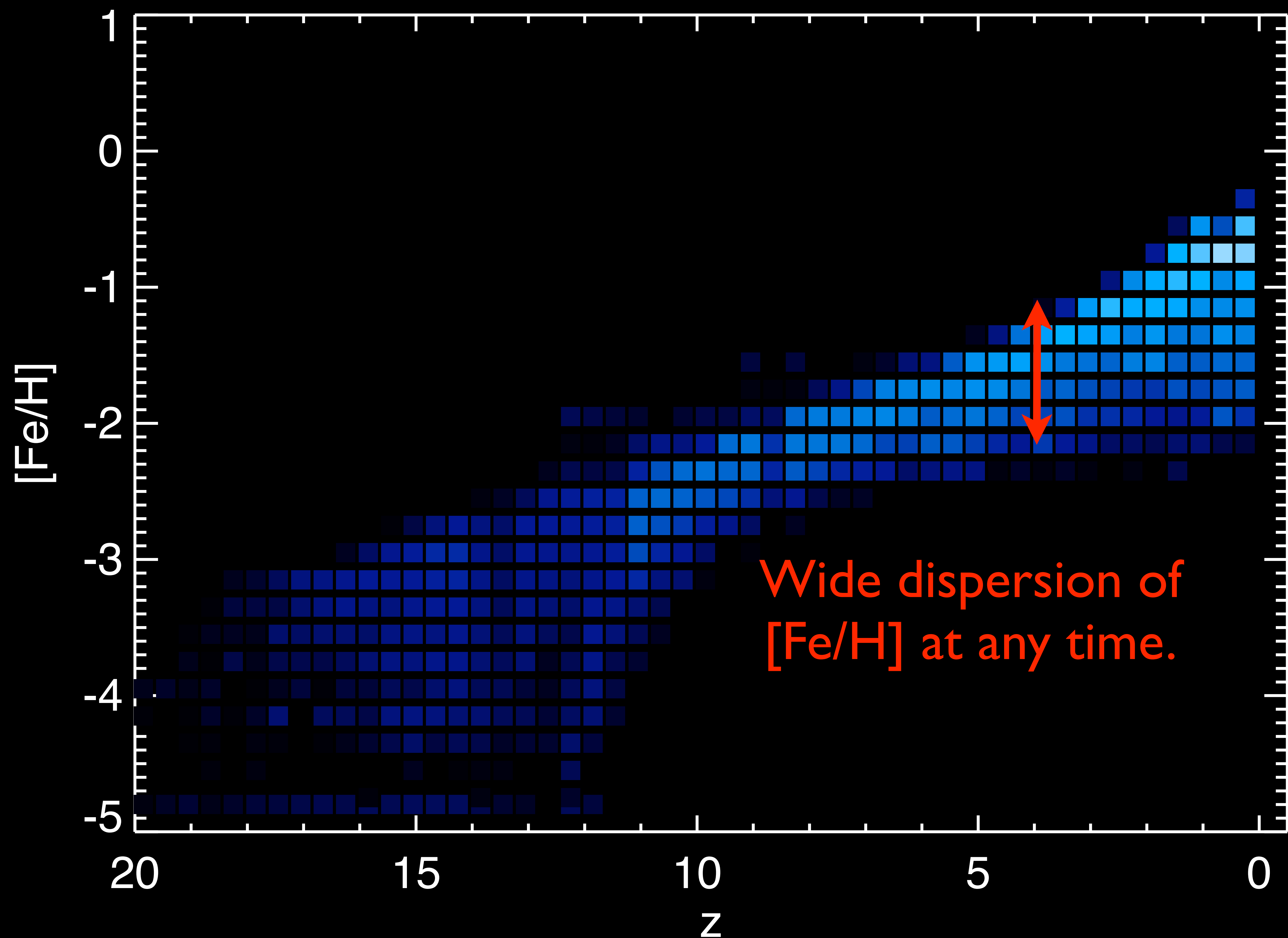

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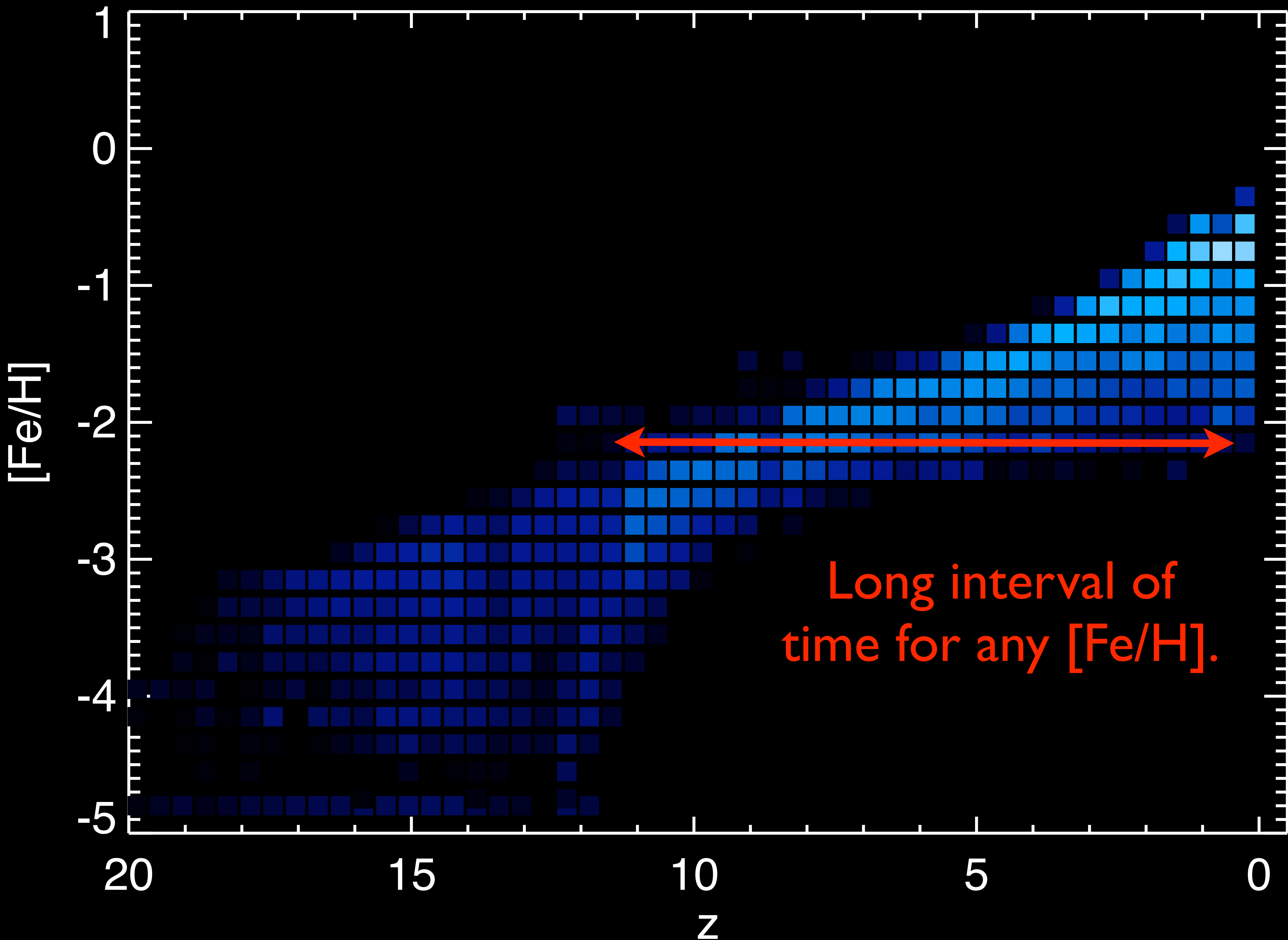

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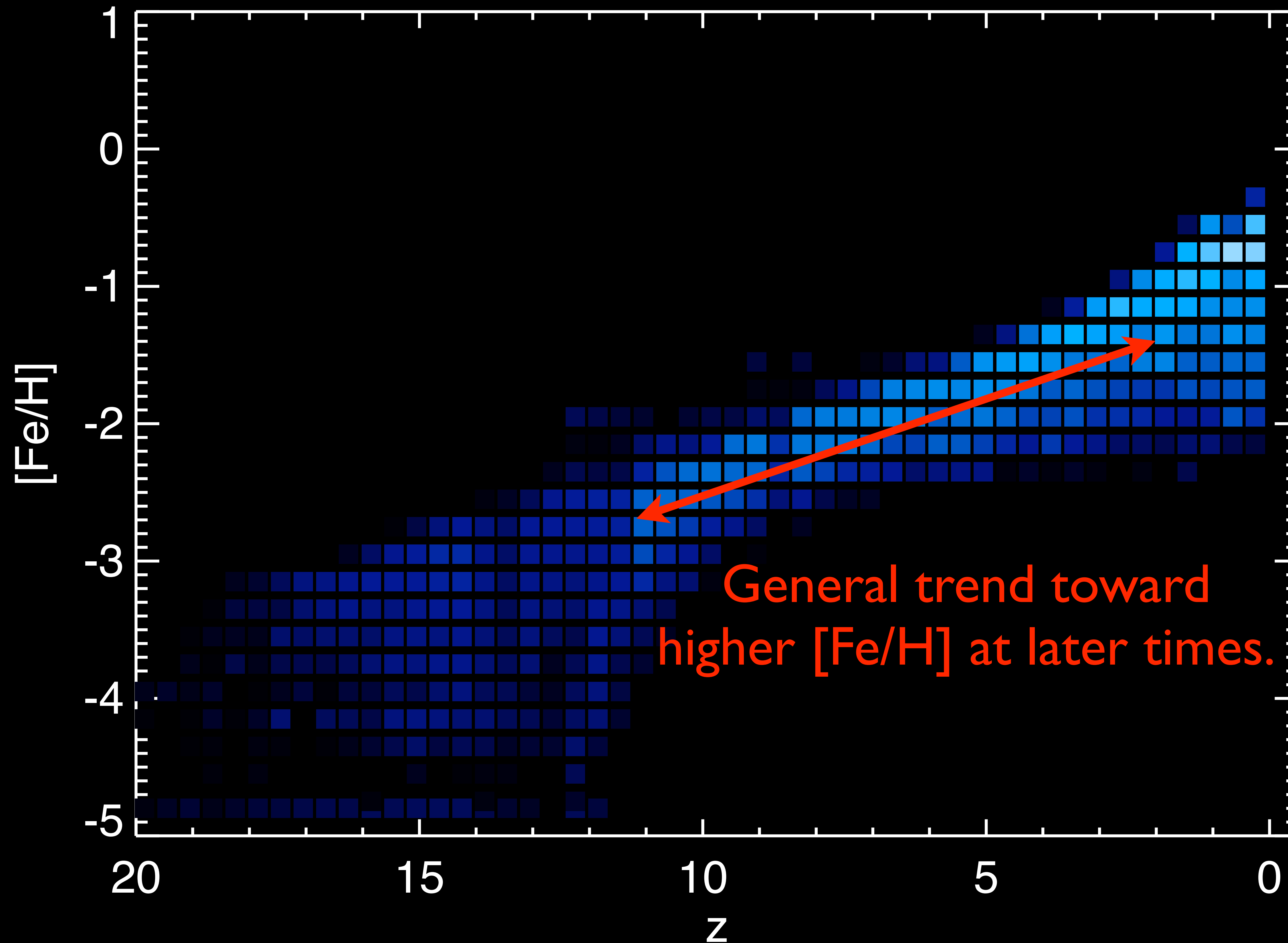

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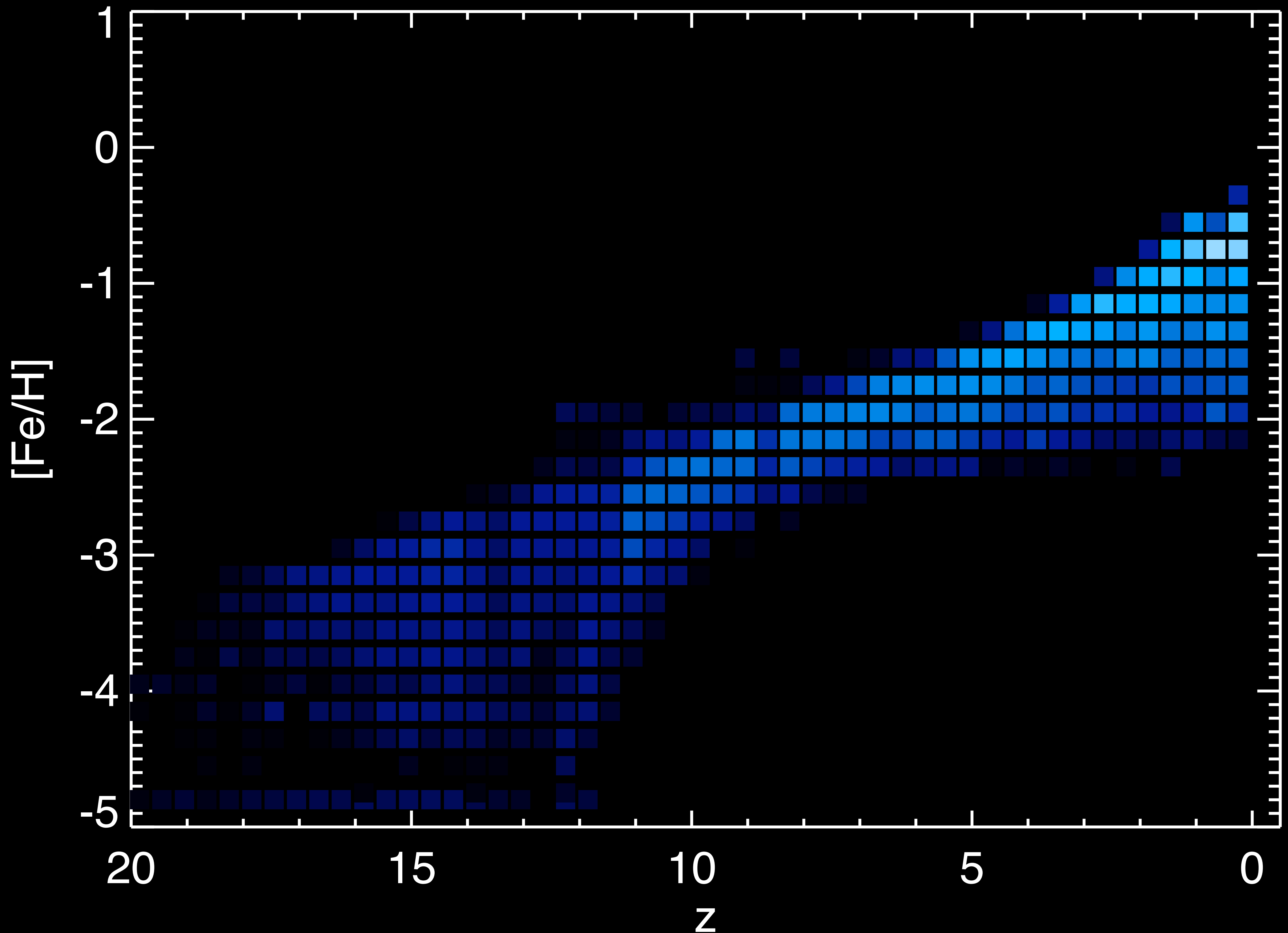


Parting Thoughts

But why, some say, the moon? Why choose this as our goal? And they may well ask why climb the highest mountain. Why, 35 years ago, fly the Atlantic? ***Why does Rice play Texas?***

We choose to go to the moon in this decade, and do the other things, not because they are easy, but because they are hard.

John F. Kennedy
September 12, 1962

October 1994: After 28 consecutive losses to the Longhorns, Rice beats Texas 19-17. I was there.

The lesson: We can go to the Moon, Rice can beat Texas, and we can find the first stars!

Three Big Ideas, Three Challenges

1. *Where can the transition be studied?*

    - We should grant that JWST will not see the first stars, and move on.

    - The fossil record is rich, and could be decisive if we learn how to read it.

2. *The CMB-IMF as a mediator of the transition.*

    - It's there. What effect did it have?

    - How can we test the hypothesis at high-redshift?

3. *The "second stars" are in, but not of, the Galactic bulge.*

    - Can we access the fossil record there as we now do in the halo?

    - What role can JWST play in this endeavor? NIRSpec!!

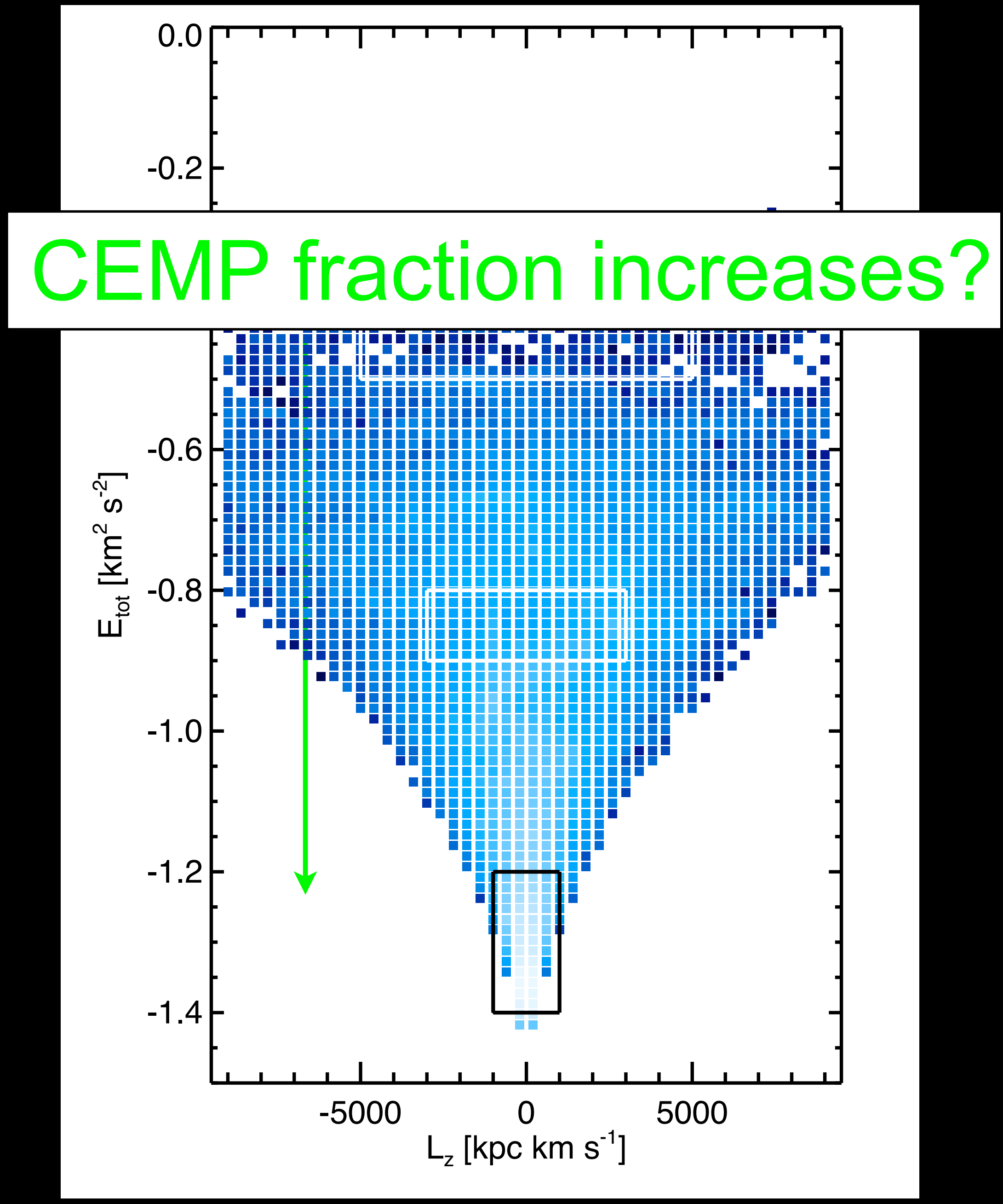
The implication of the CMB-IMF is that . . .

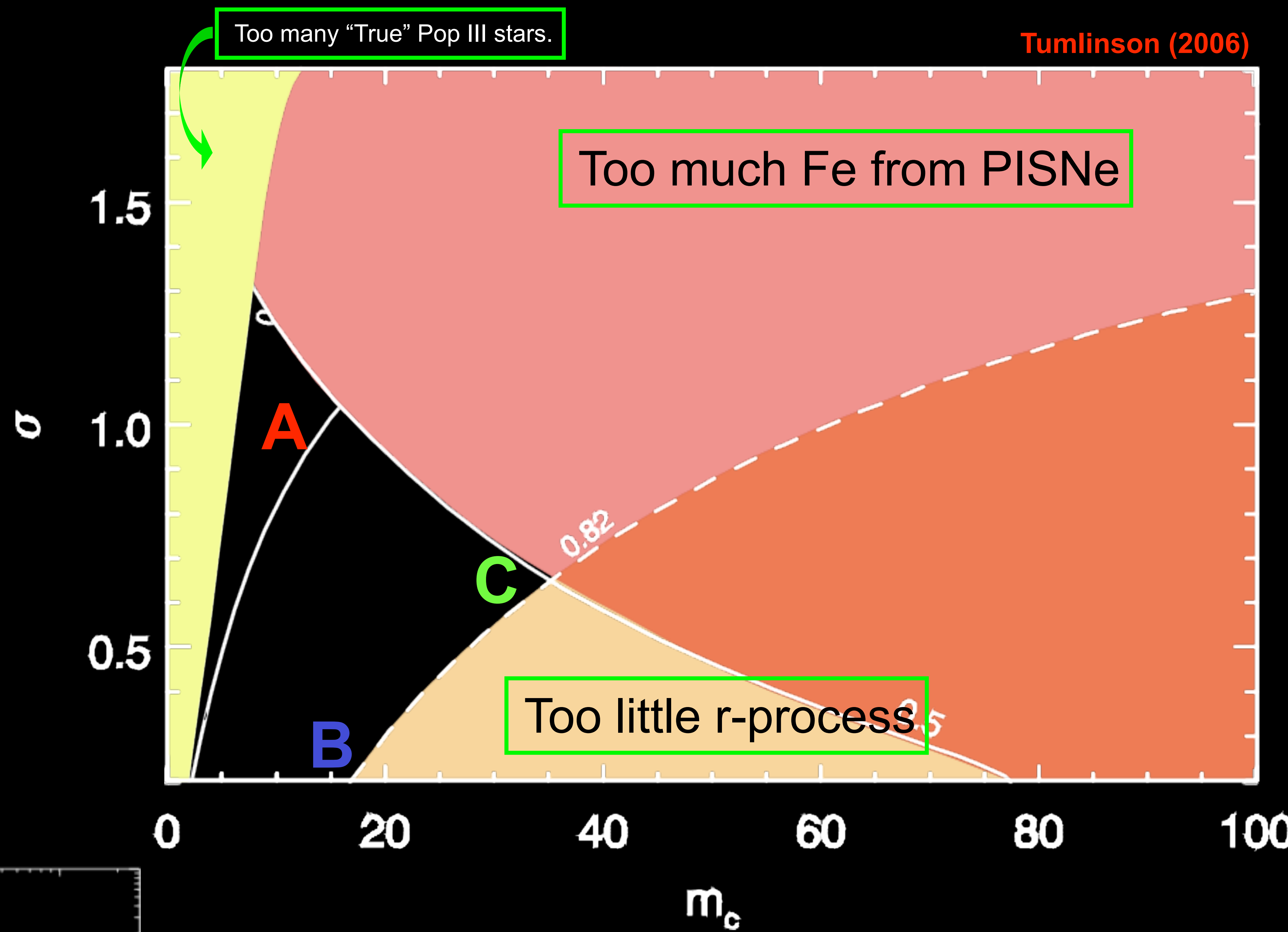
. . . earlier stellar populations see a hotter CMB, have a high characteristic mass, and so exhibit a higher fraction of CEMPs.

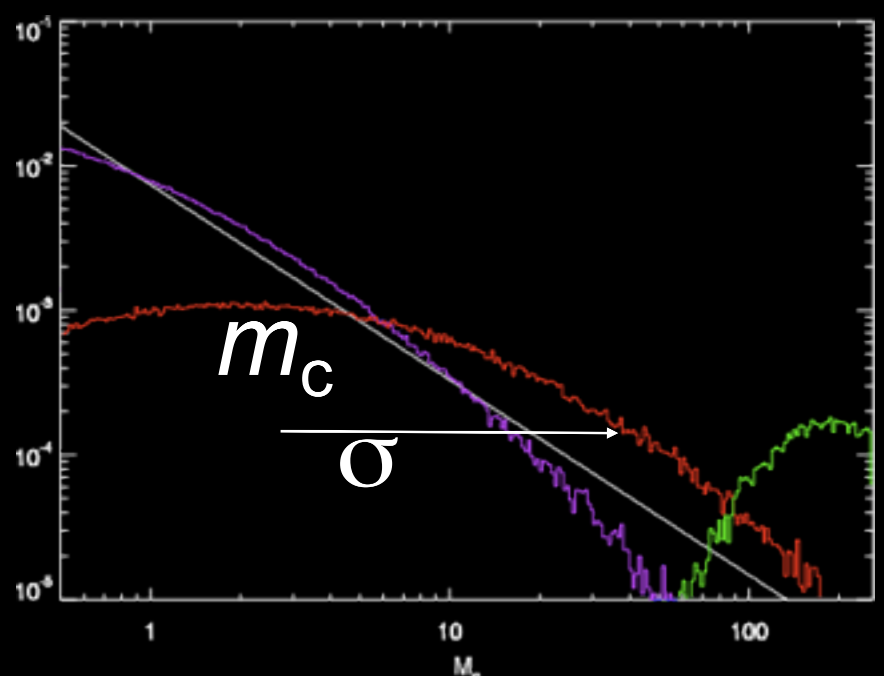
. . . while later stellar populations see a cooler CMB, have a lower characteristic mass, and so exhibit a lower fraction of CEMPs.

Observational needs:

- obtain reliable C/Fe ratios in a large number of stars with [Fe/H] < -1.
- Measure CEMP fraction f_{CEMP} as a function of orbital binding energy.
- Measured Ba, Eu, Sr abundances in as many as possible, to distinguish CEMP-s stars, which are very likely binaries, from CEMP-no stars, which may have another formation channel.
- At the very least, assess whether this CEMP phenomenon exists and/or changes character in the innermost halo.

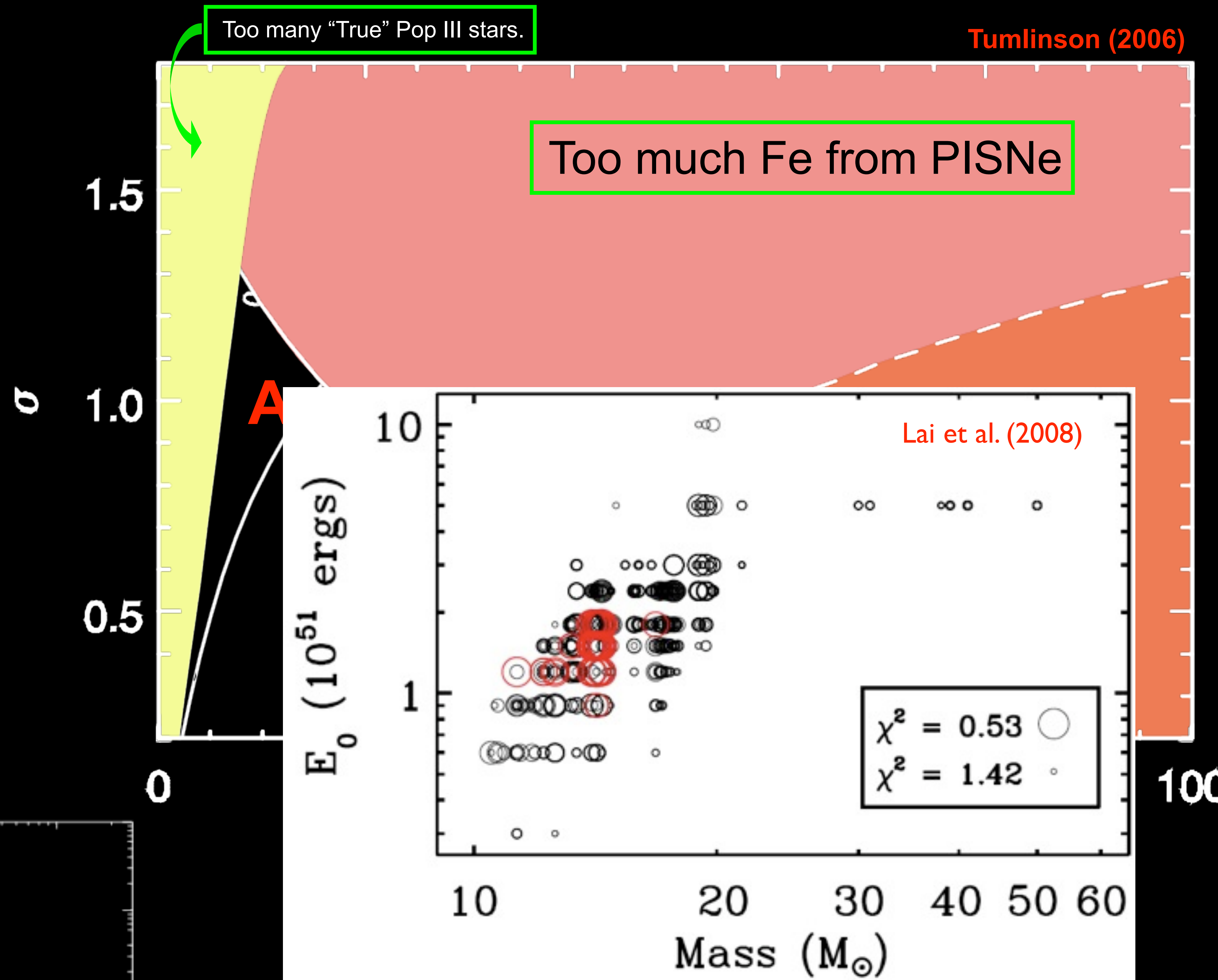


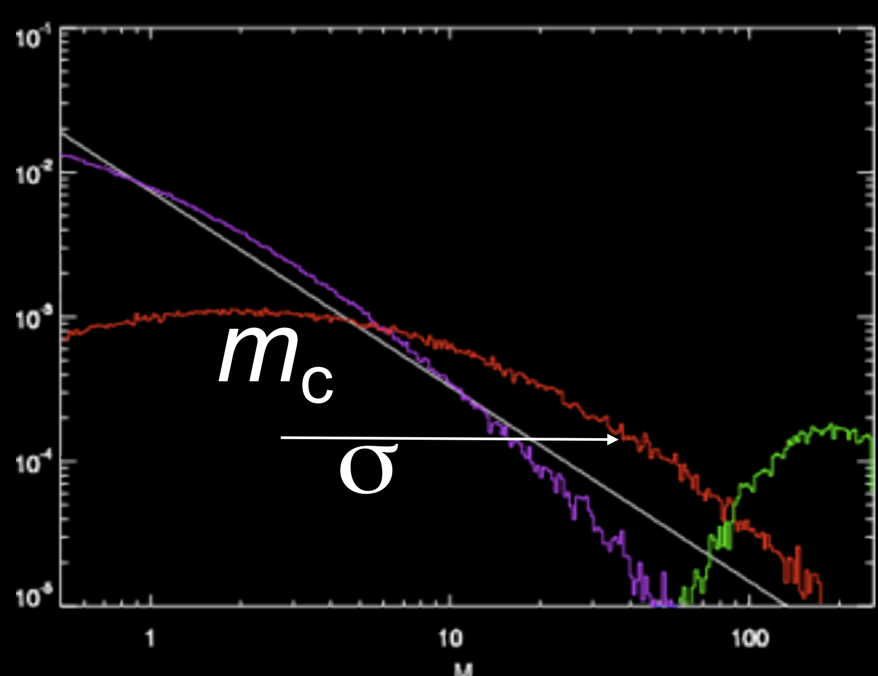




Lognormal IMF

$$\ln\left(\frac{dN}{d\ln M}\right) = A - \frac{1}{2\langle\sigma\rangle^2}\left[\ln\left(\frac{m}{m_c}\right)\right]^2$$





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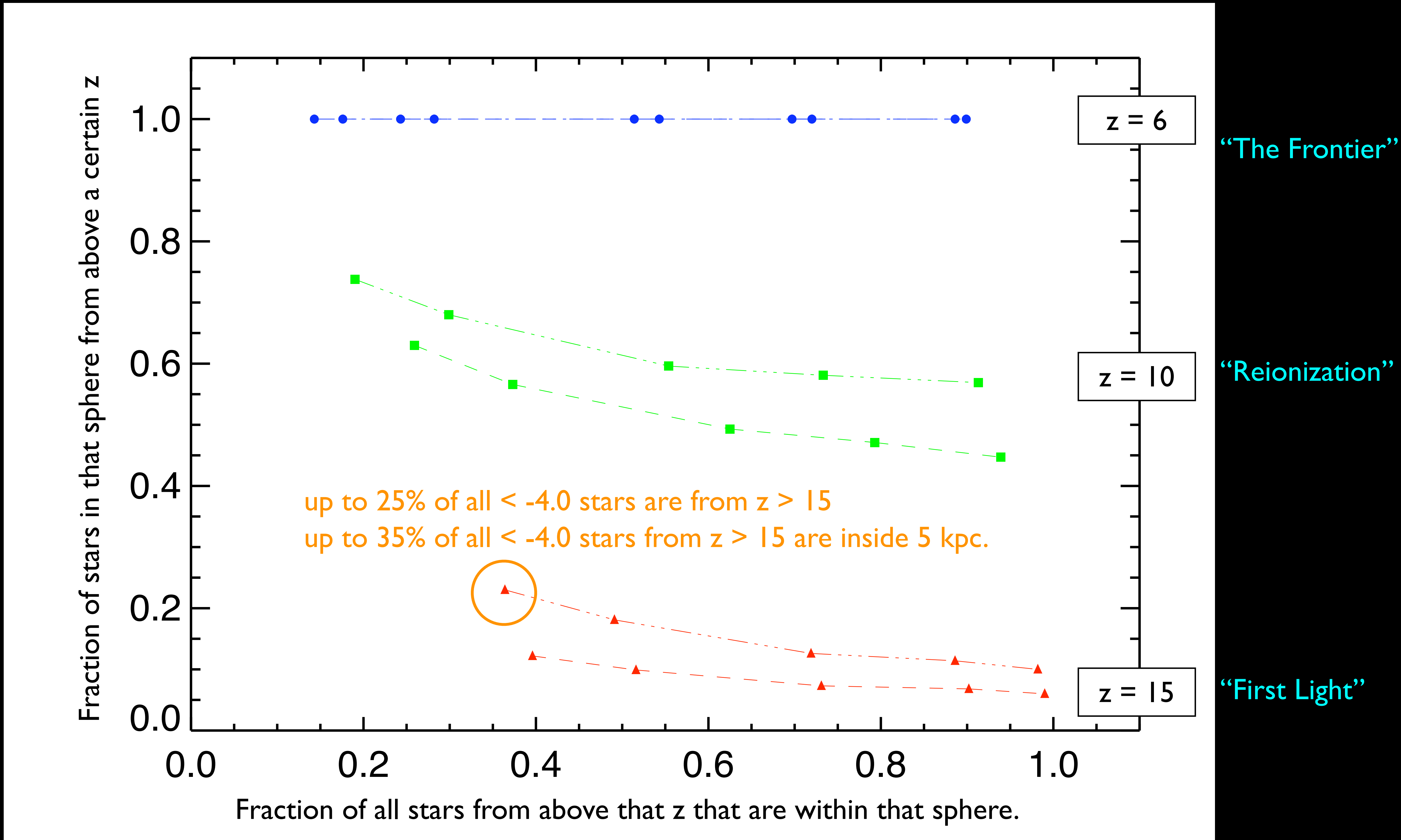

Take spheres of R around the Galactic Center

Purity = fraction of stars inside R from above a certain redshift z

Representativeness = fraction of all stars from above that z that are within that sphere.

2MASS vs. the Second Stars