The First Galaxies and the Fossil Record: Challenges for the Next Decade

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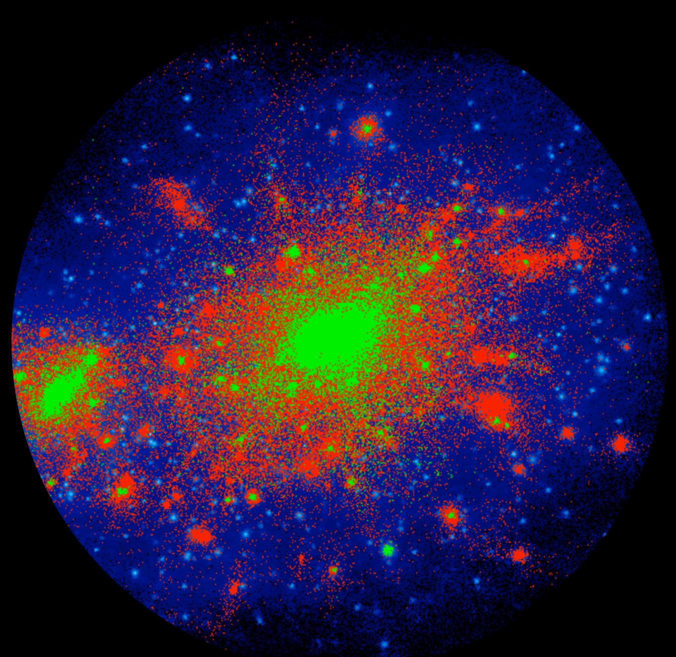
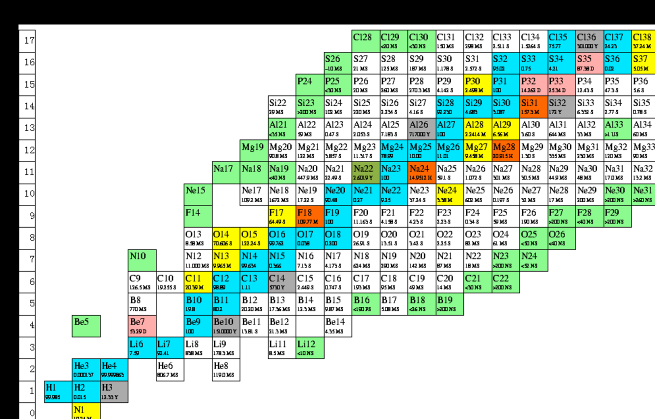
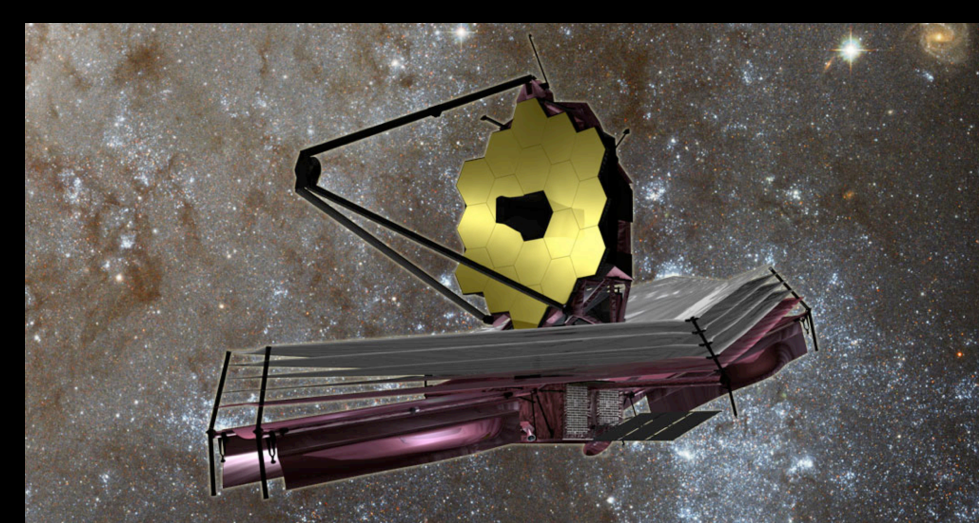
SPACE TELESCOPE SCIENCE INSTITUTE

April 29, 2010

Theme: To uncover the first stars and galaxies, we need a new and improved synthesis of nuclear physics, structure formation, and chemical evolution.







Motivation

Why pursue the fossil record?

Education

Pose the problem and survey three basic approaches.

Illustration

Three case studies that mix progress and ignorance.

Imagination

Where we need to go from here.

Why Pursue the Fossil Record?

We want “to understand how the first stars and galaxies formed, and how they change over time into the objects recognized in the present Universe.” (NASA Strategic Research Objective 3D.2)

For many astronomers, this means “deep fields” to study galaxy light at high redshift, and to examine their luminosity, mass, star formation history, and other properties of the population.

This frontier was recently advanced to z ~ 8 by Hubble’s new Wide Field Camera 3, giving a small taste of what JWST offers.

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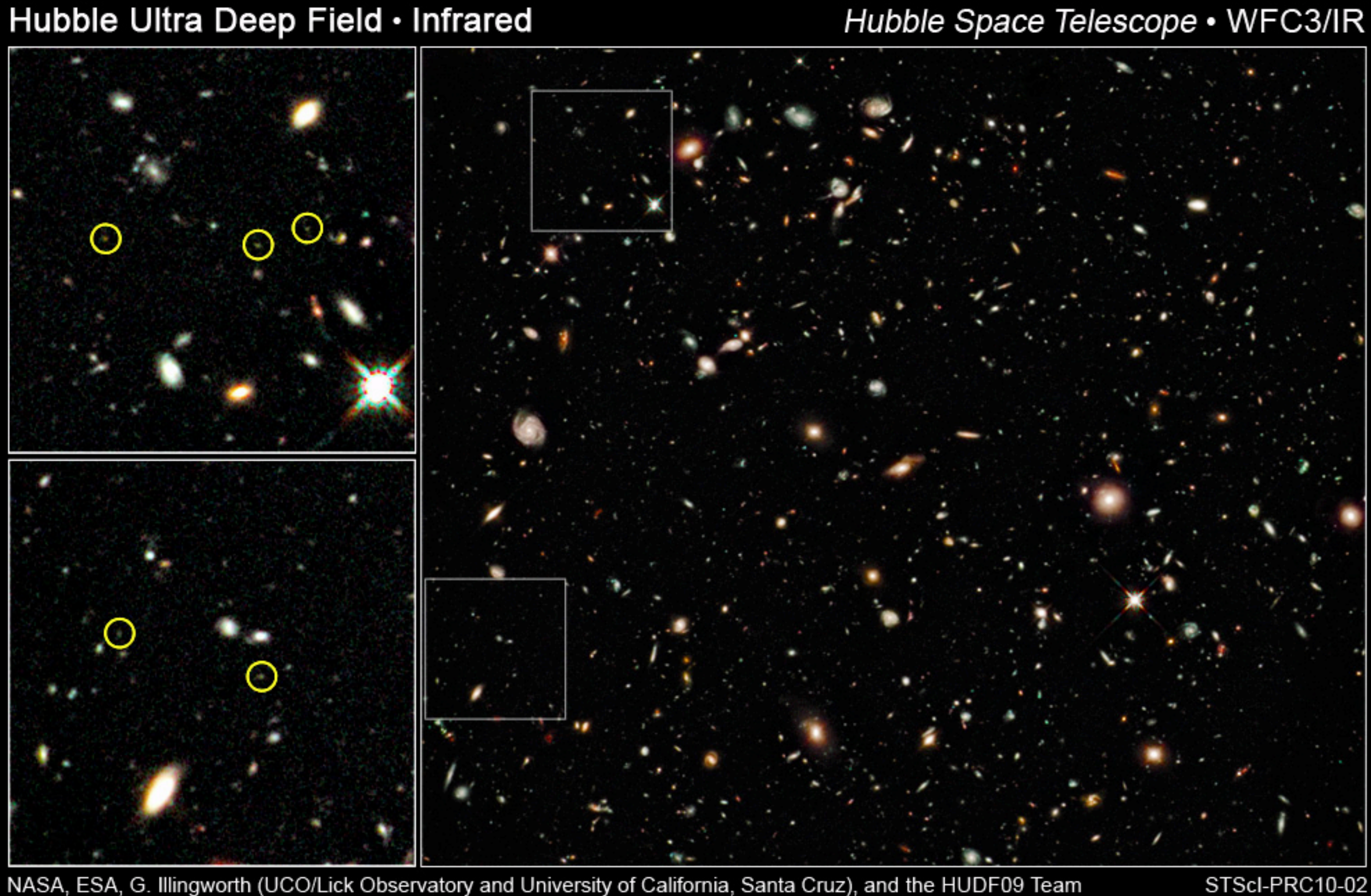

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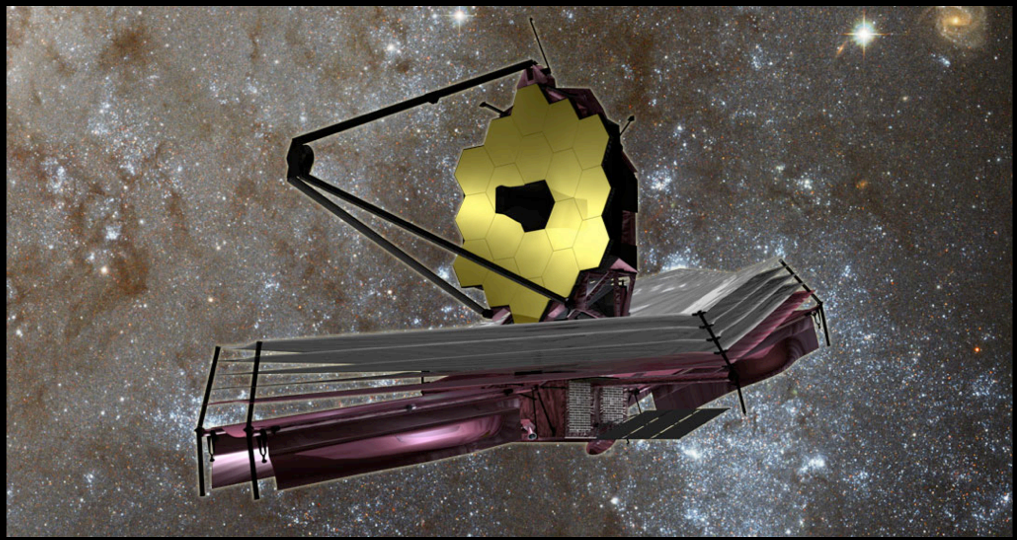

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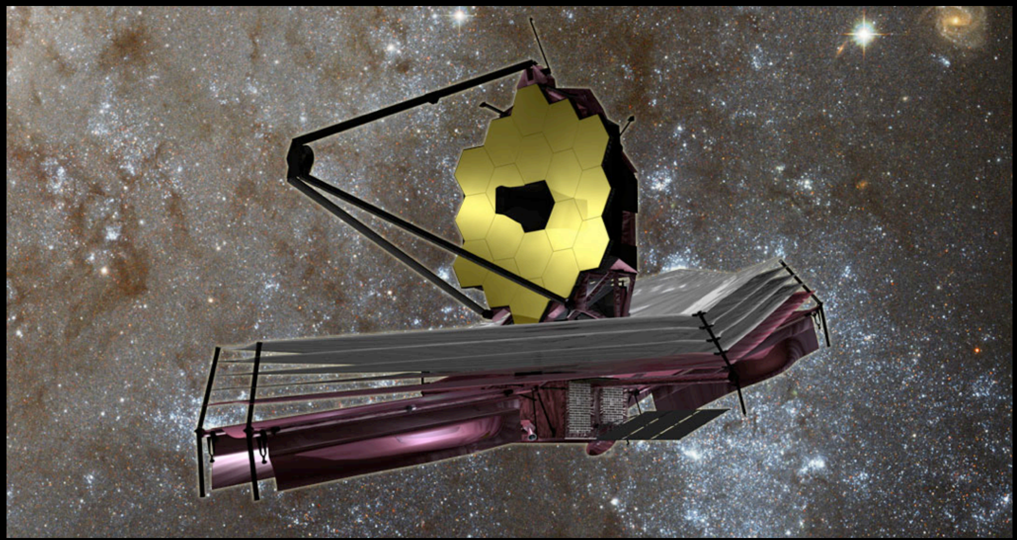

But . . .

Motivation

Won’t JWST See the First Stars?

First Light and Reionization :
open questions in the post-JWST era

Massimo Stiavelli
STScI

and

John Mather (NASA/GSFC, chair)
Mark Clampin (NASA/GSFC)
Rene Doyon (U. of Montreal)
Kathy Flanagan (STScI)
Marijn Franx (Leiden U.)
Jonathan Gardner (NASA/GSFC)
Matthew Greenhouse (NASA/GSFC)
Heidi Hammel (SSI)
John Hutchings (Herberg I. of A.)
Peter Jakobsen (ESA)
Simon Lilly (ETH-Zurich)
Jonathan Lunine (U. of Arizona)
Mark McCaughrean (U. of Exeter)
Matt Mountain (STScI)
George Rieke (U. of Arizona)
Marcia Rieke (U. of Arizona)
George Sonneborn (NASA/GSFC)
Rogier Windhorst (Arizona State U.)
Gillian Wright (UK ATC)

(the JWST Science Working Group)

Motivation

Won't JWST See the First Stars?

Isolated Population III stars will also be relatively faint in the non-ionizing continuum (AB~38.5-40 at z=10-25, compared to AB~31 achievable in 10^5 s exposures by JWST), because most of their energy output is in the ionizing continuum (Bromm et al. 2001b, Tumlinson et al. 2003) which is efficiently absorbed by the IGM. Thus, they will be impossible to detect directly with JWST.

7. Summary

The above discussion suggests that two very difficult and important questions pertaining to the First light and reionization epoch will still need to be answered in the post-JWST era: i) When and how did the first stars form? And ii) When and how did the active galactic nuclei form? This should be this field active and exciting even in the next decade. Conversely we expect that progress in our understanding of the first galaxies and reionization will be major and such that at this stage it would be hard to predict what further studies, if any, might be required.

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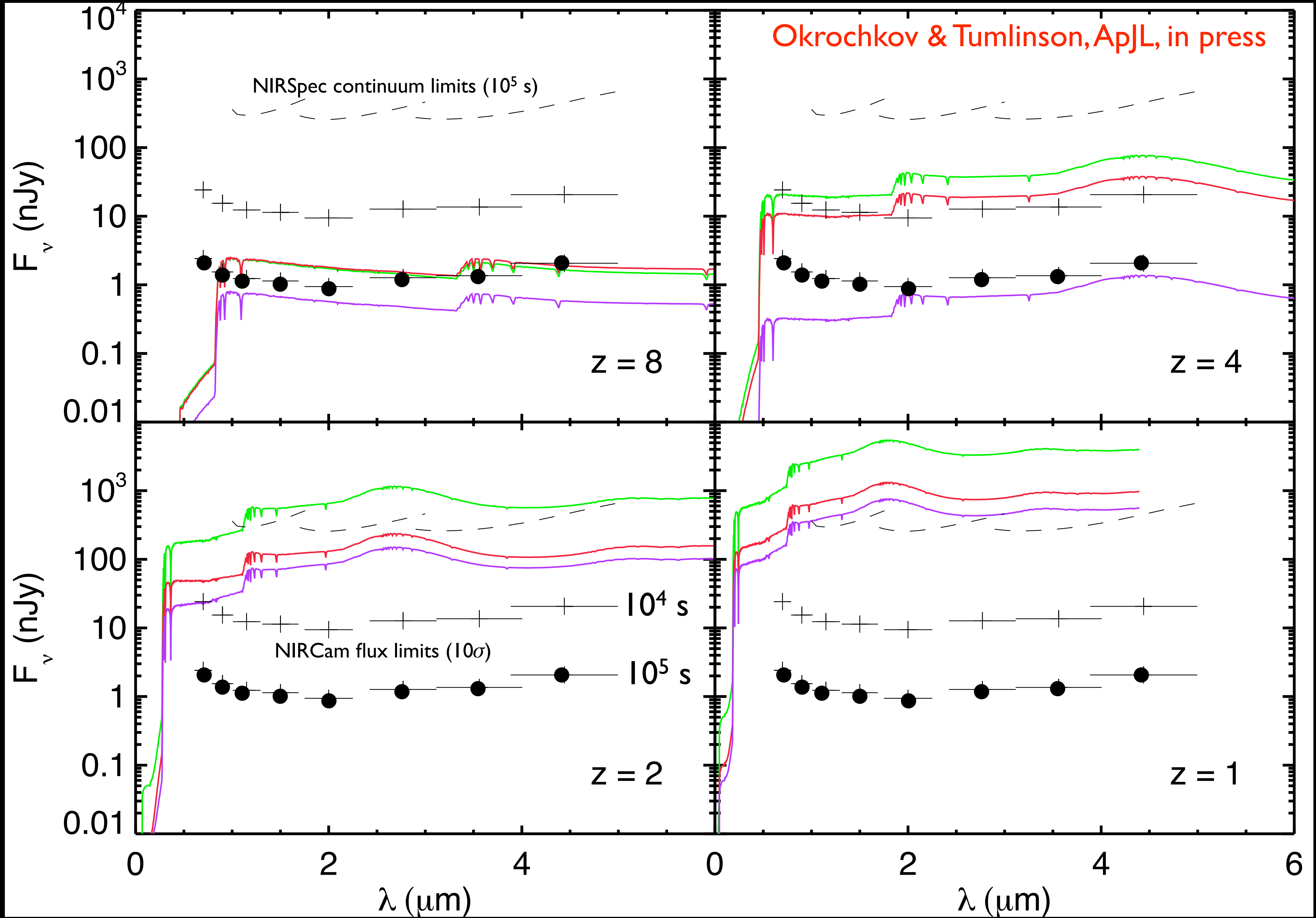
It turns out that if our theory of the first stars is correct, it will be nearly impossible to detect them directly in the high-redshift Universe!

Now what?

Motivation

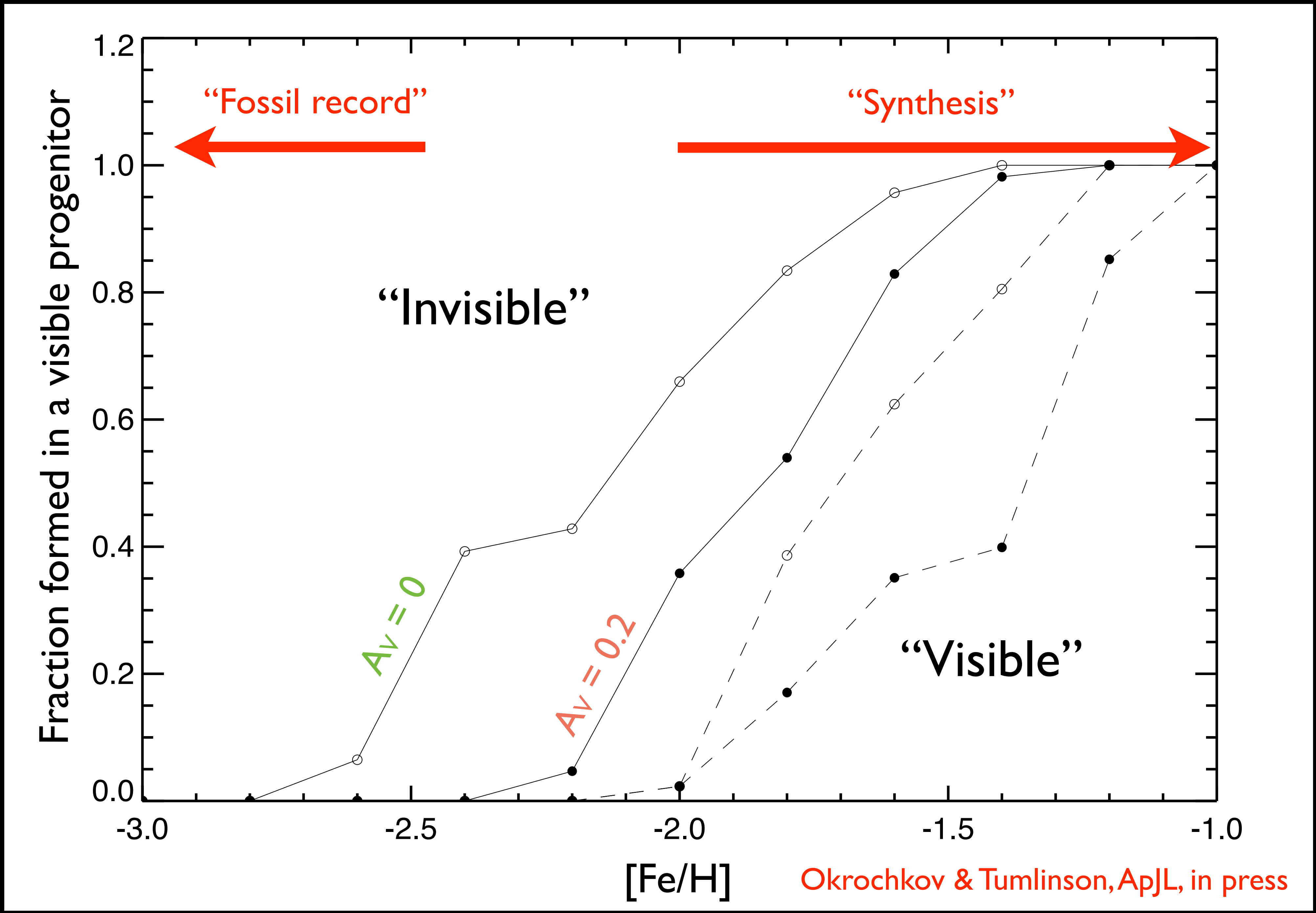
High Redshift Visibility of Milky Way Progenitors



MW progenitors visible to z ~ 6 - 8 in JWST deep fields (~dust). Each one deposits some stars into the MW halo - how do the low-z stars and the high-z visibility relate?

The High-Redshift Visibility vs. Metallicity

Motivation



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

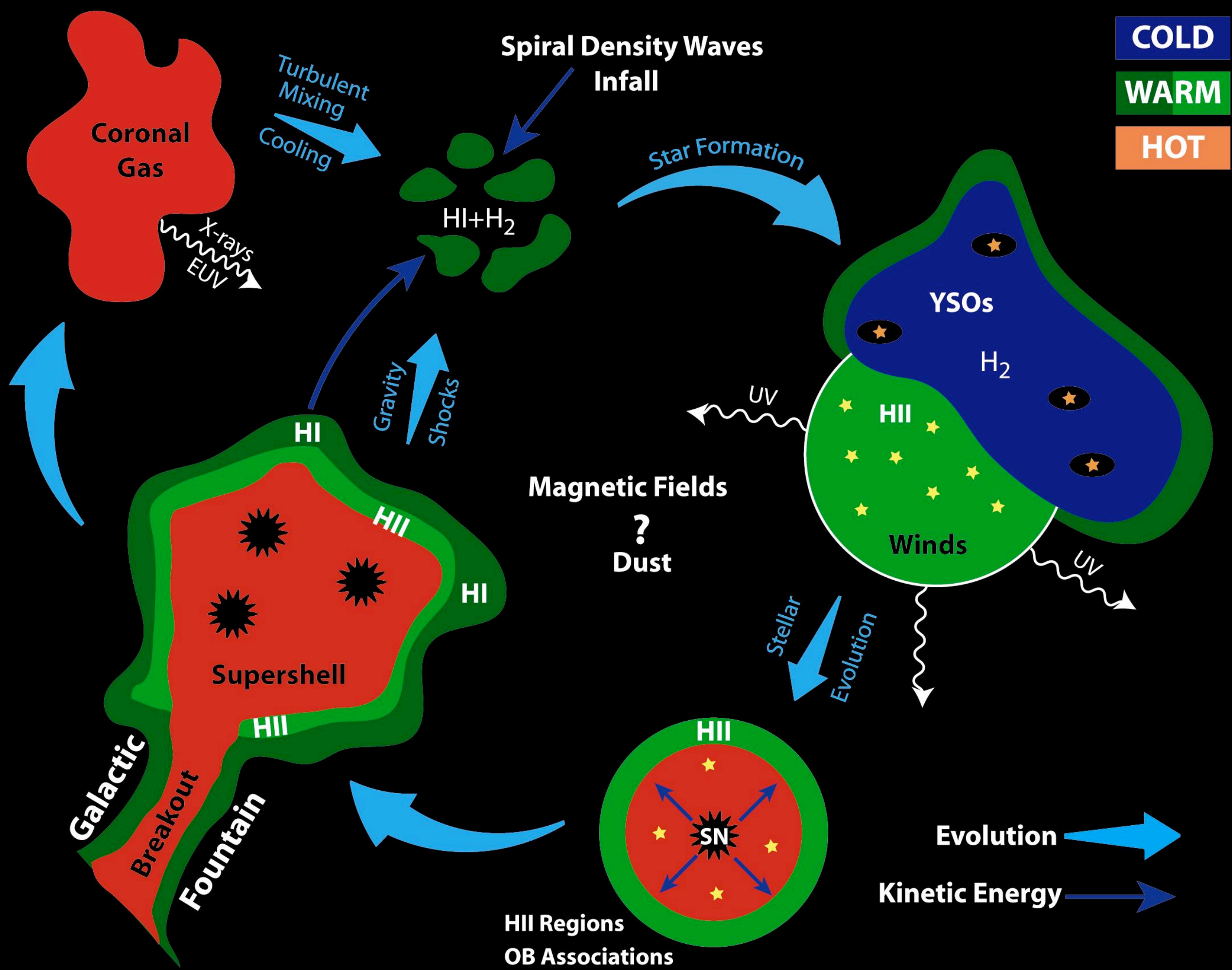
1) Those that formed in progenitors NIRCam can see: [Fe/H] ≳ -2

2) Those that formed in progenitors NIRCam cannot see: [Fe/H] ≲ -2

This is the ultimate reason to pursue the fossil record: to study galaxies we otherwise will not see!

The Problem

Observable quantities (stellar parameters, [X/Fe], orbit) are complex, emergent, stochastic functions of many coupled physical processes.



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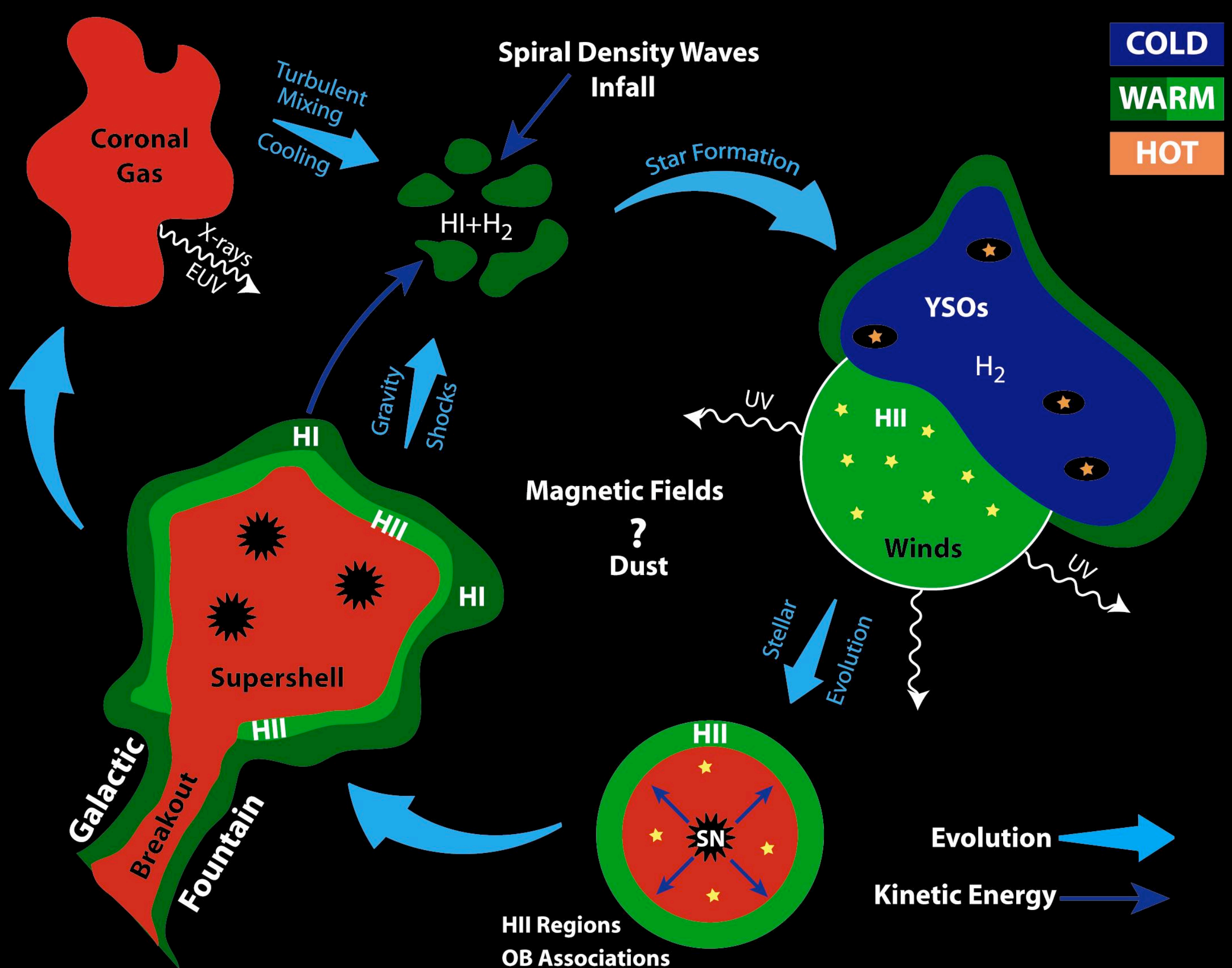

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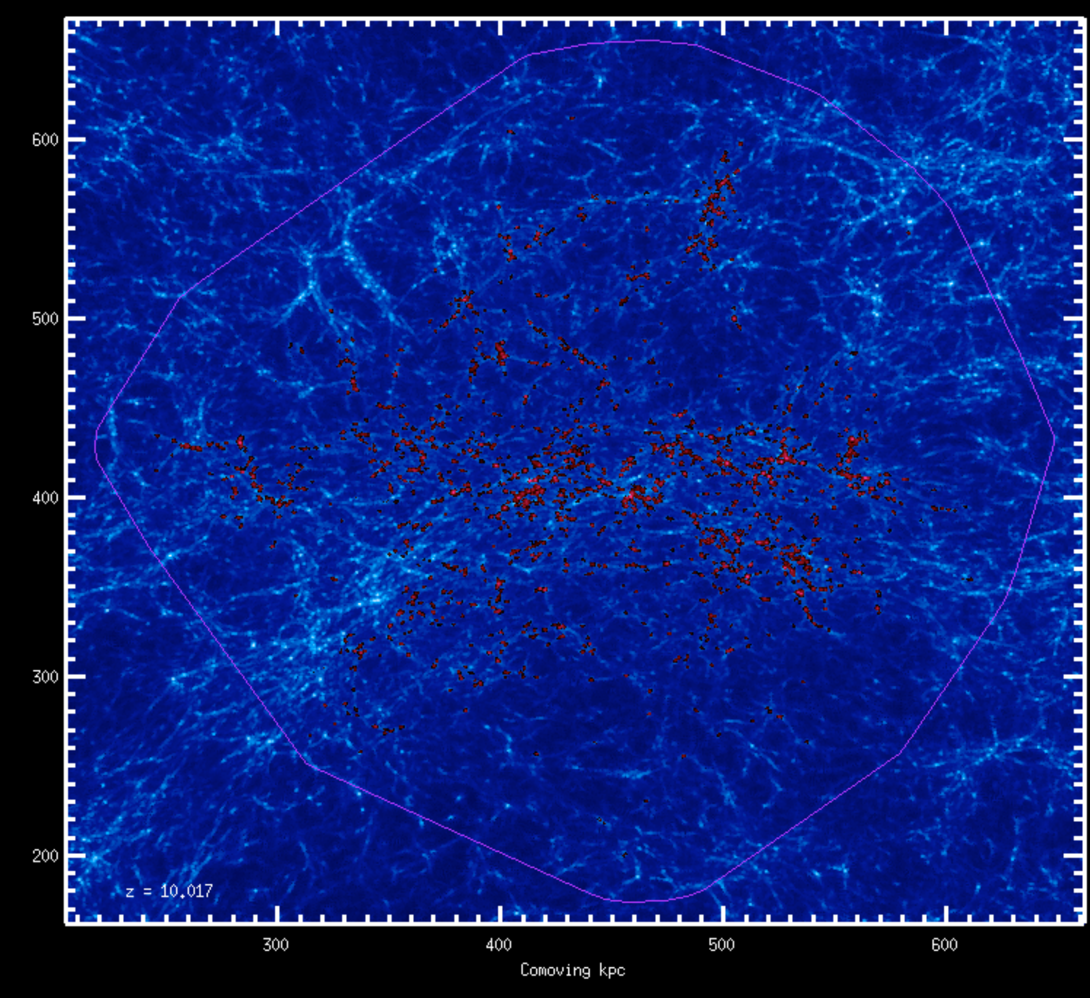

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Education

Three Basic Approaches

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Cons	1. Poor "spatial resolution" 2. Not easy to make hierarchical 3. Not really stochastic either.		

Analytic Models for Galactic Disks

Chemical evolution models for spiral disks: the Milky Way, M31 and M33 arXiv:1004.4139

M. M. Marcon-Uchida[1,2] *, F. Matteucci[1,3], and R. D. D. Costa[2]

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2. The chemical evolution model

In order to reproduce the chemical evolution of the thin-disk, we adopted an updated one-infall version of the chemical evolution model presented by Chiappini et al. (2001) (hereafter CMR2001). In this model, the galactic disk is divided into several concentric rings which evolve independently without exchange of matter.

The disk is built up in an "inside-out" scenario which is a necessary condition to reproduce the radial abundance gradients (Colavitti et al. 2008). The infall law for the thin-disk is defined as:

$$\frac{d\Sigma_I(R,t)}{dt} = B(R)e^{-\frac{(t-t_{max})}{\tau_D}} \quad (1)$$

where $\Sigma_I(R,t)$ is the gas surface density of the infall, t_{max} is the time of maximum gas accretion in the disk, set equal to 1 Gyr, coincident with the end of halo /thick disk phase and τ_D is the timescale for the infalling gas into the thin-disk. To have an inside-out formation in the disk, the timescale for the mass accretion is assumed to increase with the Galactic radius following a simple linear relation. In particular, we tested different linear relations, as we will see in table 1. The coefficient B(R) is derived from the condition that the total mass surface density at the present time in the disk is reproduced.

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According to recent studies (e.g. Romano et al. 2005) the IMF and the stellar lifetimes are responsable for the uncertanties in the chemical evolution models for the Milky Way. In this work we assumed an IMF constant in space and time and adopted the prescription from Kroupa (1993), instead of a two-slope approximation of Scalo (1986) used by CMR2001. The total surface mass density distribution for the Galactic disk was assumed to be exponential with scale length $R_D = 3.5$ kpc normalized to $\Sigma_D(R_\odot, t_{Gal}) = 54 M_\odot pc^{-2}$ (Romano et al. 2000)

$$\Sigma_D(R, t_{Gal}) = \Sigma_0(0, t_{Gal})e^{-R/R_D} \quad (3)$$

Apart from the IMF, this model differs from the one of the CMR2001 model in: (1) the oxygen yields for massive stars that are supposed to be metallicity-dependent and taken from Woosley & Weaver (1995), as suggested in François et al. (2004); (2) the stellar lifetimes of Schaller et al (1992) instead of the Maeder & Meynet (1989); and (3) the solar abundances are those from Asplund et al. (2009).

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Galactic disk divided into rings. . .

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2. The chemical evolution model

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The disk is built up in an "inside-out" scenario which is a necessary condition to reproduce the radial abundance gradients (Colavitti et al. 2008). The infall law for the thin-disk is defined as:

$$\frac{d\Sigma_I(R,t)}{dt} = B(R)e^{-\frac{(t-t_{max})}{\tau_D}} \quad (1)$$

where $\Sigma_I(R,t)$ is the gas surface density of the infall, t_{max} is the time of maximum gas accretion in the disk, set equal to 1 Gyr, coincident with the end of halo /thick disk phase and τ_D is the timescale for the infalling gas into the thin-disk. To have an inside-out formation in the disk, the timescale for the mass accretion is assumed to increase with the Galactic radius following a simple linear relation. In particular, we tested different linear relations, as we will see in table 1. The coefficient B(R) is derived from the condition that the total mass surface density at the present time in the disk is reproduced.

In order to make the program as simple and generalized as possible, we used a SFR proportional to a Schmidt law:

$$\Psi(r,t) \propto \nu\Sigma^k_{gas}(r,t) \quad (2)$$

where ν is the efficiency in the star formation process and the surface gas density is represented by $\Sigma_{gas}(r,t)$ while the exponent k is equal to 1.5 (see Kennicutt 1998 and Chiappini et

Fig. 1. Distribution of dwarf stars in the solar vicinity obtained by using different IMFs. Scalo 1986 (dotted line) and Kroupa et al. (1993) (dashed line) compared to the observational data from Holmberg et al. 2007 (solid line). The label "New tau" indicates that we have used the $\tau(R)$ law of this paper shown in Table 1.

According to recent studies (e.g. Romano et al. 2005) the IMF and the stellar lifetimes are responsable for the uncertanties in the chemical evolution models for the Milky Way. In this work we assumed an IMF constant in space and time and adopted the prescription from Kroupa (1993), instead of a two-slope approximation of Scalo (1986) used by CMR2001. The total surface mass density distribution for the Galactic disk was assumed to be exponential with scale length $R_D = 3.5$ kpc normalized to $\Sigma_D(R_\odot, t_{Gal}) = 54 M_\odot pc^{-2}$ (Romano et al. 2000)

$$\Sigma_D(R, t_{Gal}) = \Sigma_0(0, t_{Gal})e^{-R/R_D} \quad (3)$$

Apart from the IMF, this model differs from the one of the CMR2001 model in: (1) the oxygen yields for massive stars that are supposed to be metallicity-dependent and taken from Woosley & Weaver (1995), as suggested in François et al. (2004); (2) the stellar lifetimes of Schaller et al (1992) instead of the Maeder & Meynet (1989); and (3) the solar abundances are those from Asplund et al. (2009).

2.1. The Milky Way

We computed the model for the Milky Way several times with star formation efficiency of $1 Gyr^{-1}$ and different time scales for the infalling gas into the disk (τ). Table 1 shows the coefficients for the linear equations adopted for $\tau(R)$. Figure 1 contains the predictions for the dwarf metallicity distribution in the

Analytic Models for Galactic Disks

Chemical evolution models for spiral disks: the Milky Way, M31 and M33 arXiv:1004.4139

M. M. Marcon-Uchida[1,2] *, F. Matteucci[1,3], and R. D. D. Costa[2]

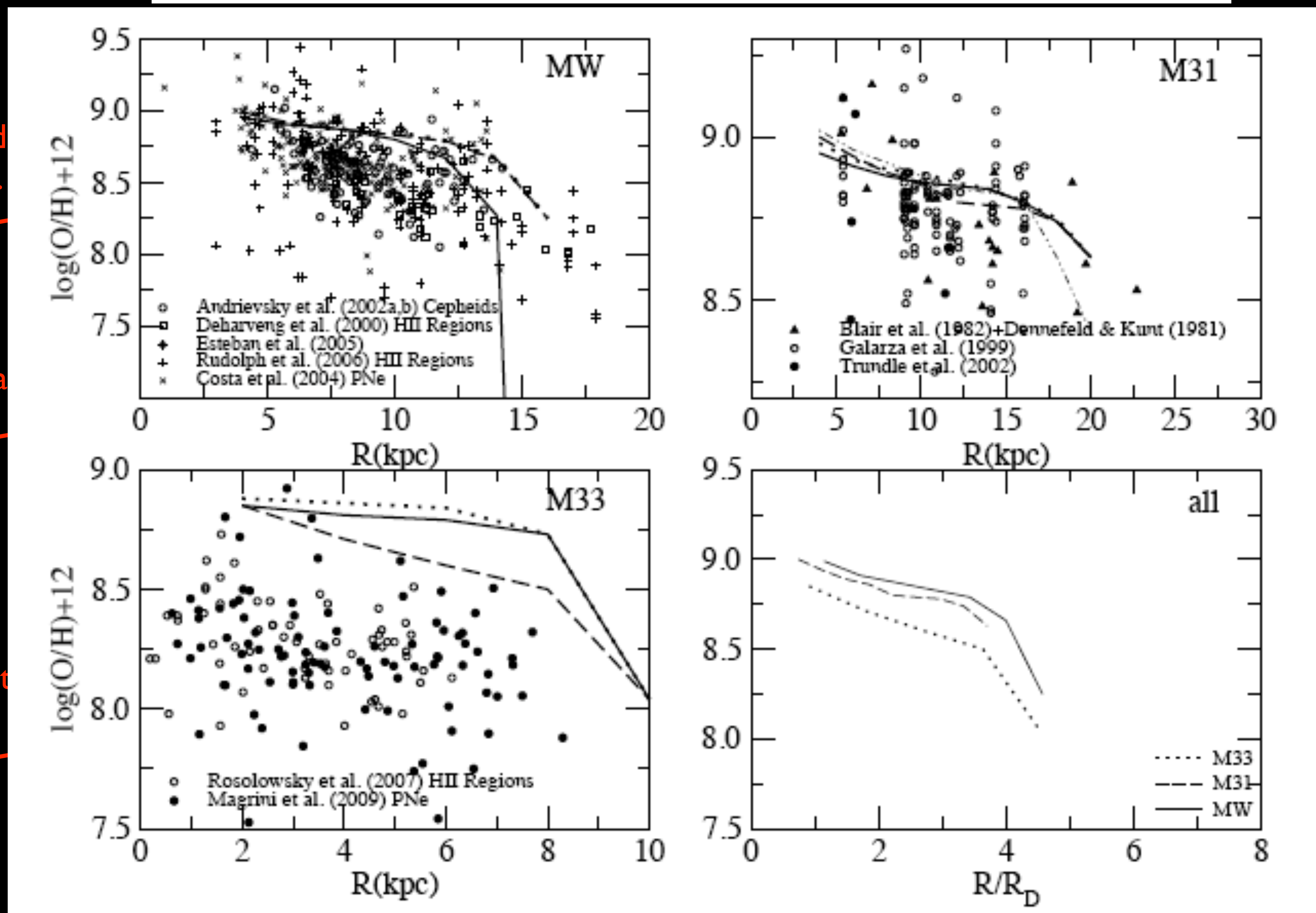
[1] Dipartimento di Fisica, Sezione di Astronomia, Università di Trieste, via G.B. Tiepolo 11, I-34131, Trieste, Italy
[2] Instituto de Astronomia, Geofísica e Ciências Atmosféricas (IAG), Universidade de São Paulo, Rua do Matão, 1226 Cidade Universitária, São Paulo - SP, 05508-900, Brazil
[3] I.N.A.F. Osservatorio Astronomico di Trieste, via G.B. Tiepolo 11, I-34131, Trieste, Italy

Galactic disk d
into rings.

Infall tracked into ea

Star formation rate t
in each ring

odel yields put in



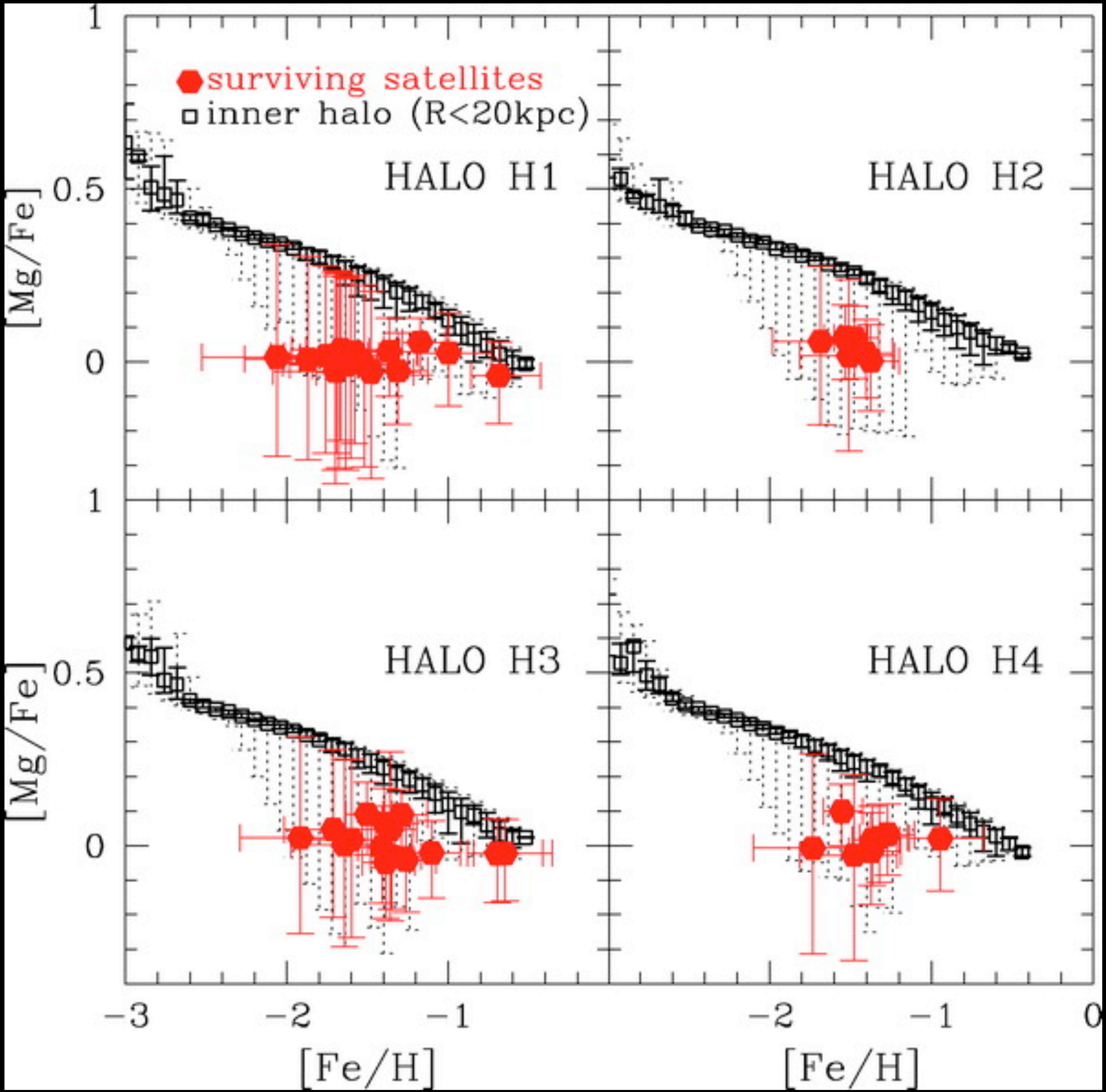
Radial distribution of oxygen abundance shows that these models are good for large gas budgets, long timescales, and no hierarchy.

Education

Three Basic Approaches

	Analytic	Semi-Analytic	Numerical
History	Oldest form, dating from 1960s and 70s in mature form (Tinsley, Cameron, Truran, many others).	Began to appear in the 2000s with relatively cheap N-body simulations and semi-analytic techniques for modeling galaxy populations. Scale these down to single galaxies and you get the picture.	
Basics	Study mass budgets in gas and various chemical elements; simple set of differential equations with yields as inputs; allow “inflow” and “outflow” from reservoir as needed.	Use the traditional tools of chemical evolution theory as always used in the analytic theory, but relate the gas mass budgets and star formation histories back to the mass assembly history of halos and subhalos specified by ΛCDM. Tag stellar populations back to particles in the N-body simulation.	
Pros	1. Simple mathematics 2. Simple parameterizations 3. Easy to understand results 4. Good for “bulk” chemical evolution (like SNIa/II or r/s balance), on >kpc / galaxy scales.	1. Simple mathematics 2. Simple parameterizations 3. Naturally incorporates the hierarchical structure formation 4. Relatively cheap to run and to do “parameter space” studies.	
Cons	1. Poor “spatial resolution” 2. Not easy to make hierarchical 3. Not really stochastic either.	1. Poor “resolution” 2. N-body DM simulations do not explicitly calculate gas dynamics 3. Lack of self-consistent gas physics causes proliferation of parameters.	

A Key Victory for Semi-Analytics



Bullock & Johnston (2005)
Font et al. (2006; 2008)
Johnston et al. (2008)

Synthetic stellar halos built on top of N-body simulations of an isolated halo.

Shows convincingly that the low [α/Fe] ratios of surviving Galactic satellites are consistent with a hierarchical formation scenario.

These models have also been extensively mined for other results, such as [α/Fe] vs. surface brightness maps.

Education

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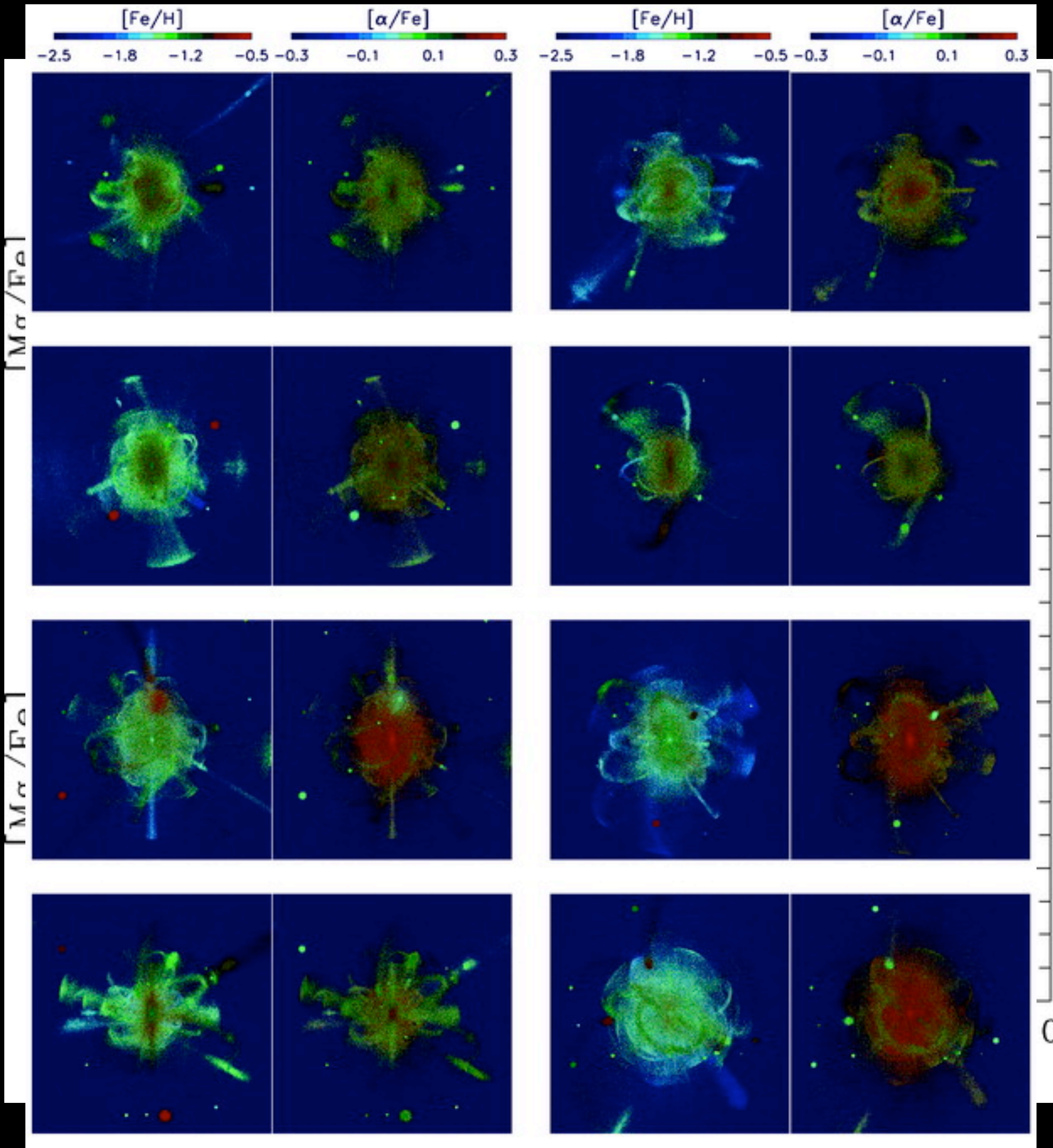

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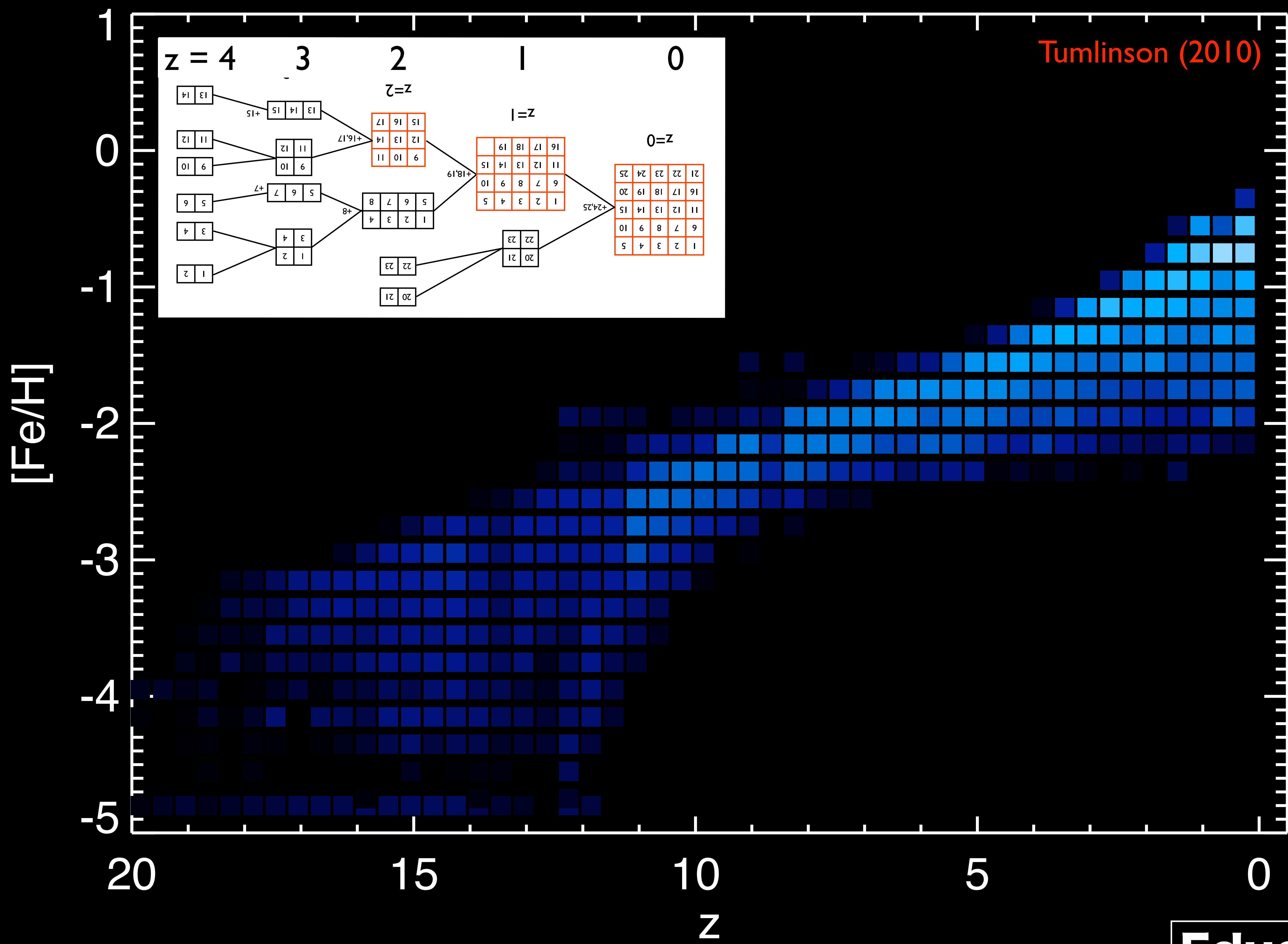
Education

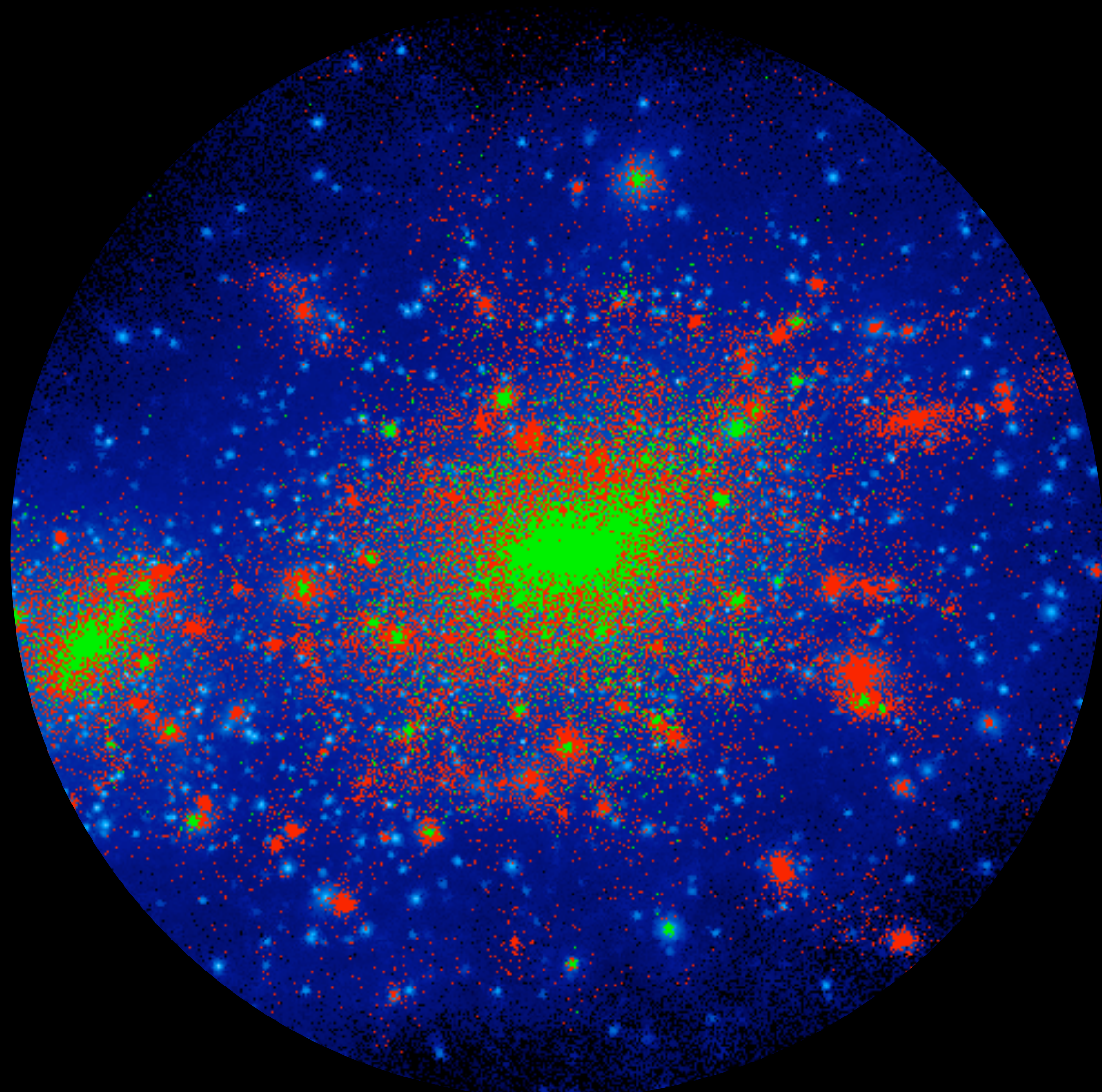
Hierarchical, Stochastic Models and the MW



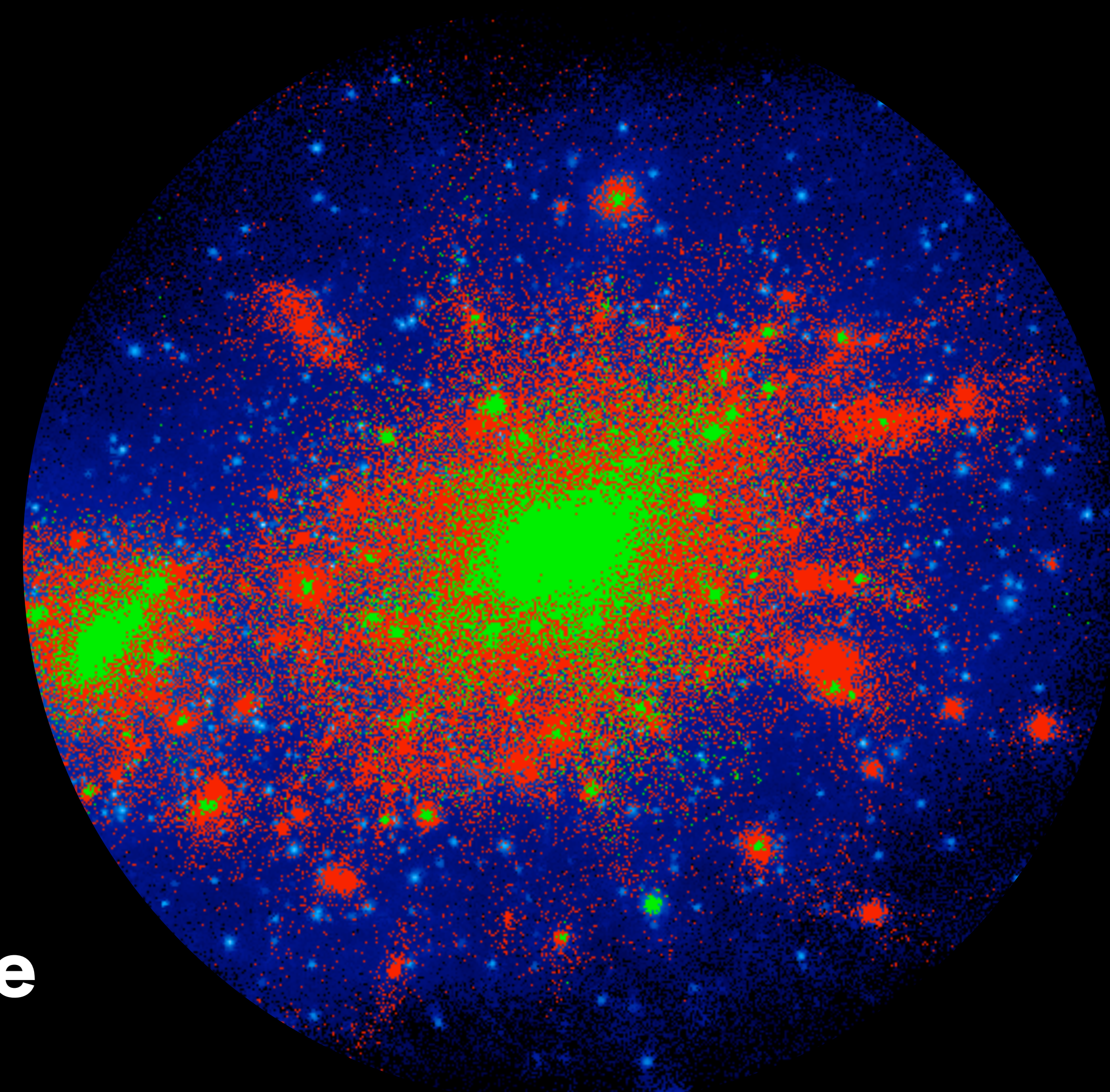
Education

Semi-Analytics and the First Galaxies

stars formed z > 10
stars formed at all z



[Fe/H] < -3.5



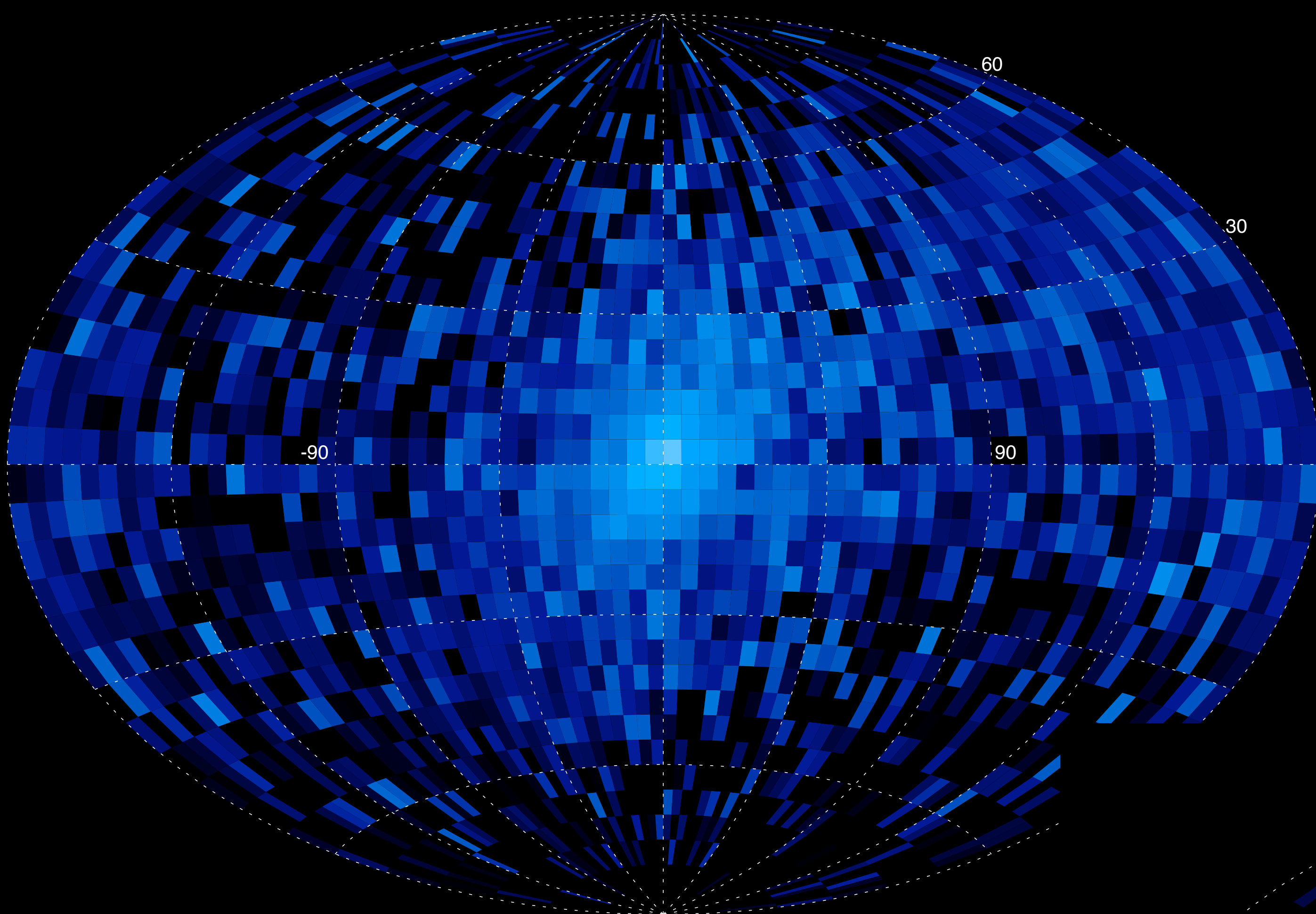
[Fe/H] < -2.0

Chronologically older stars are more centrally concentrated.

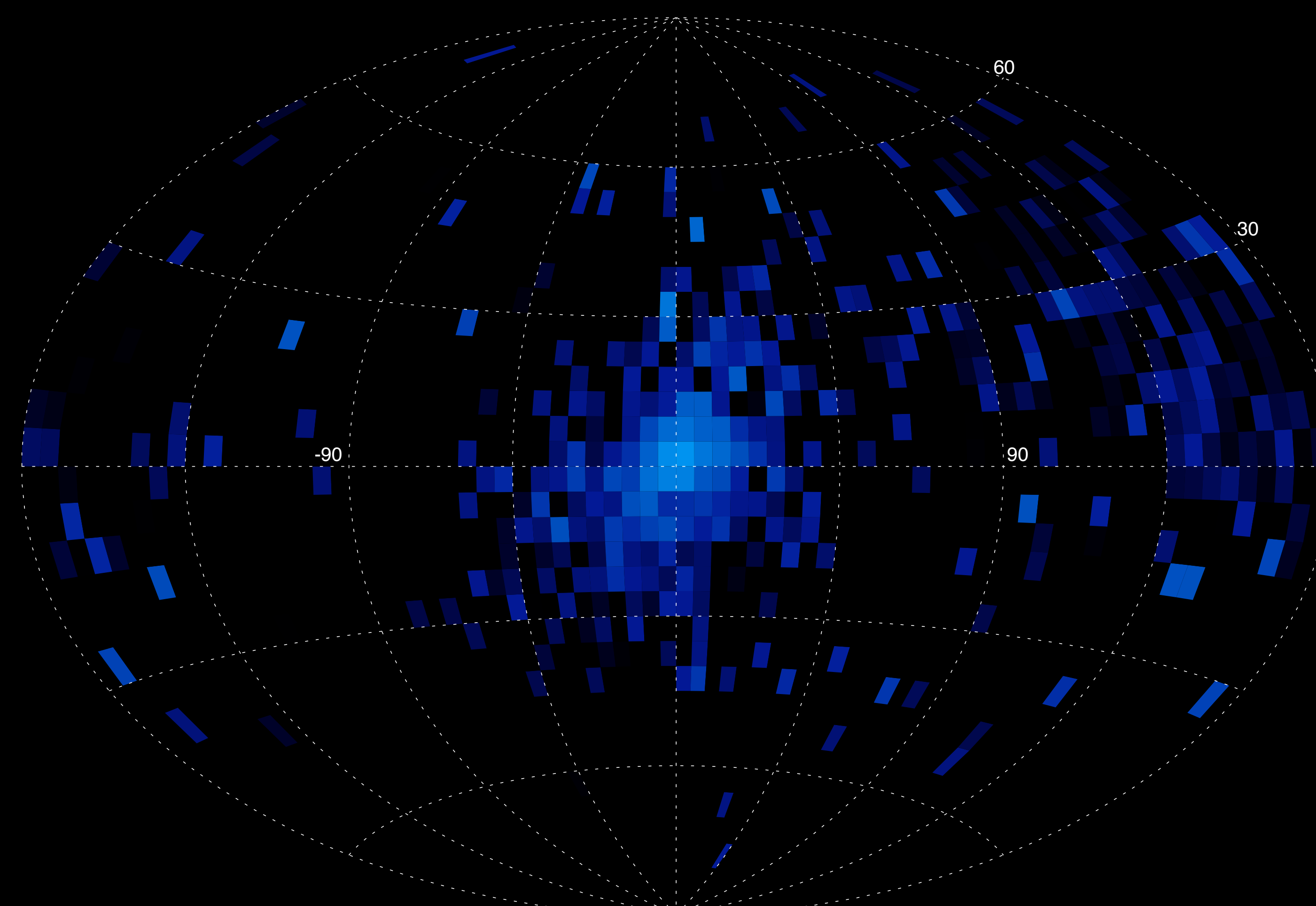
Education

Tumlinson (2010)

All Stars with [Fe/H] < -3



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



The most ancient stars are “in the bulge” but not “of the bulge”.

Education

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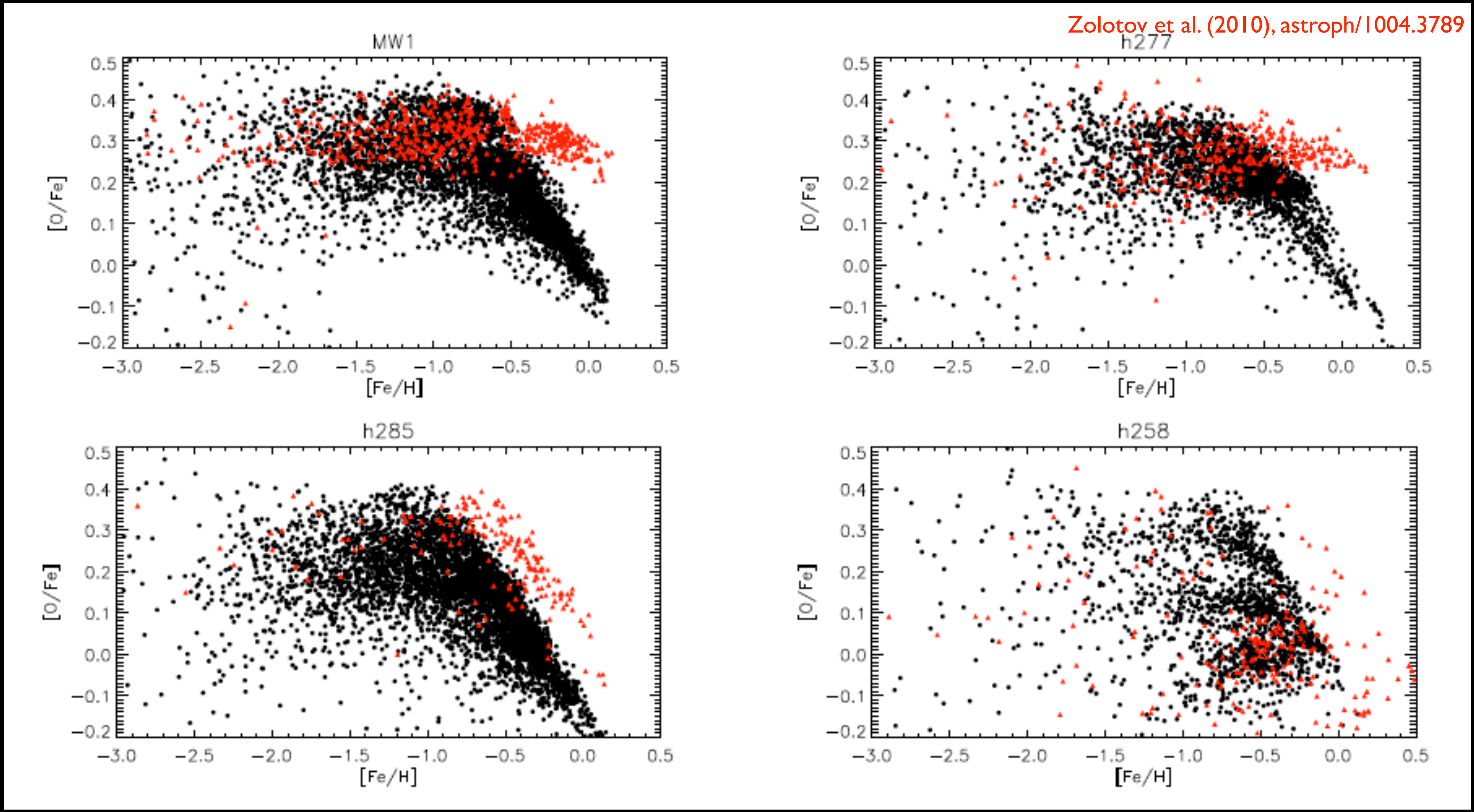
Pros	1. Simple mathematics 2. Simple parameterizations 3. Easy to understand results 4. Good for "bulk" chemical evolution (like SNIa/II or r/s balance), on >kpc / galaxy scales.	1. Simple mathematics 2. Simple parameterizations 3. Naturally incorporates the hierarchical structure formation 4. Relatively cheap to run and to do "parameter space" studies.	1. Best spatial resolution 2. Fully consistent with cosmological structure formation. 3. Most self-consistent treatment. 4. Should be excellent at the level of small galaxies.
Cons	1. Poor "spatial resolution" 2. Not easy to make hierarchical 3. Not really stochastic either.	1. Poor "resolution" 2. N-body DM simulations do not explicitly calculate gas dynamics 3. Lack of self-consistent gas physics causes proliferation of parameters.	1. Expensive in CPUs and memory. 2. Usually possible to run only a few highly-resolved simulations/yr. 3. Uncertain "subgrid" physics must still be parameterized.

A Late-Breaking Example from GASOLINE

Education



Red: "In situ" star in the inner MW halo.

Black: "Accreted" stars from disrupted dwarf galaxies.

The two populations are chemically distinct because the later-merging subhalos form stars for longer and evolve more toward AGB / SN Ia yields (just as Font showed for dwarf galaxies).

+ Can track "in situ stars"

- Can track only one element!

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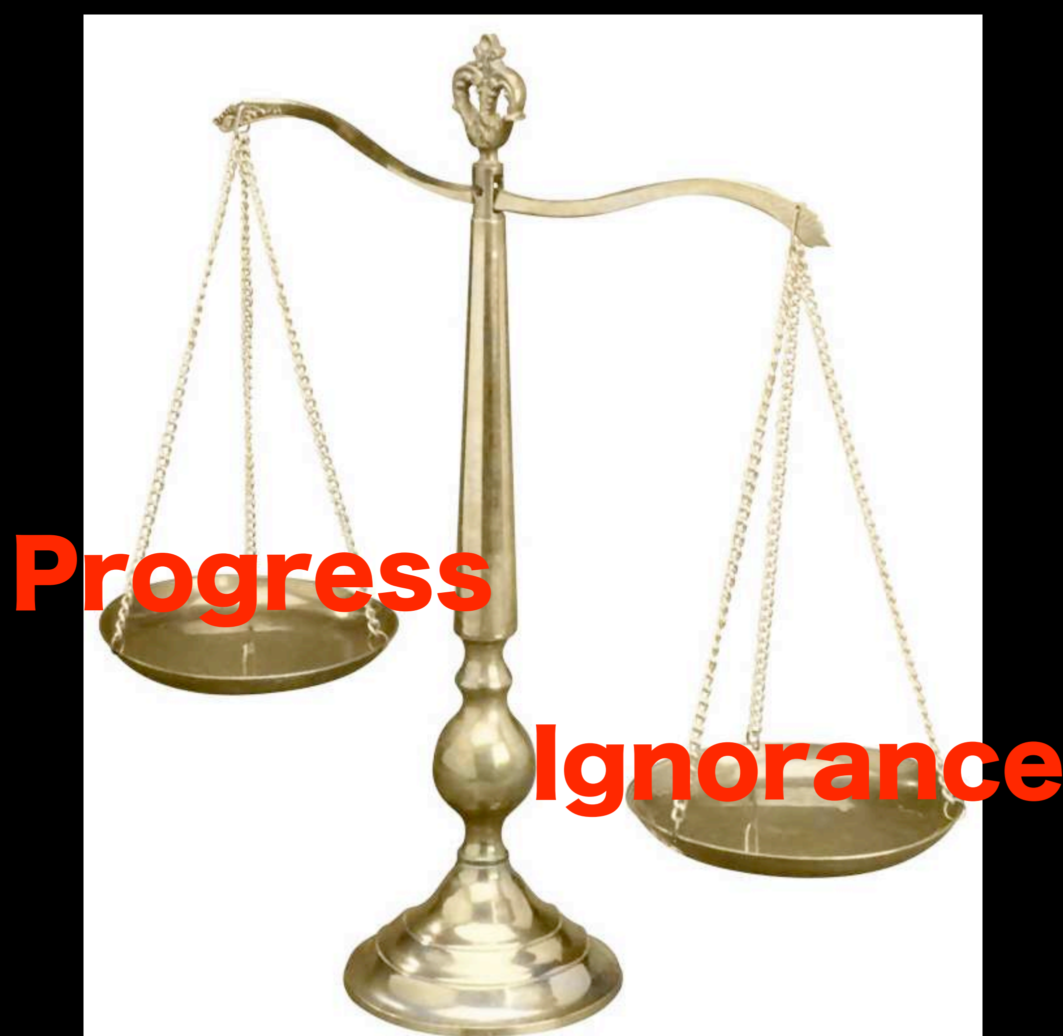
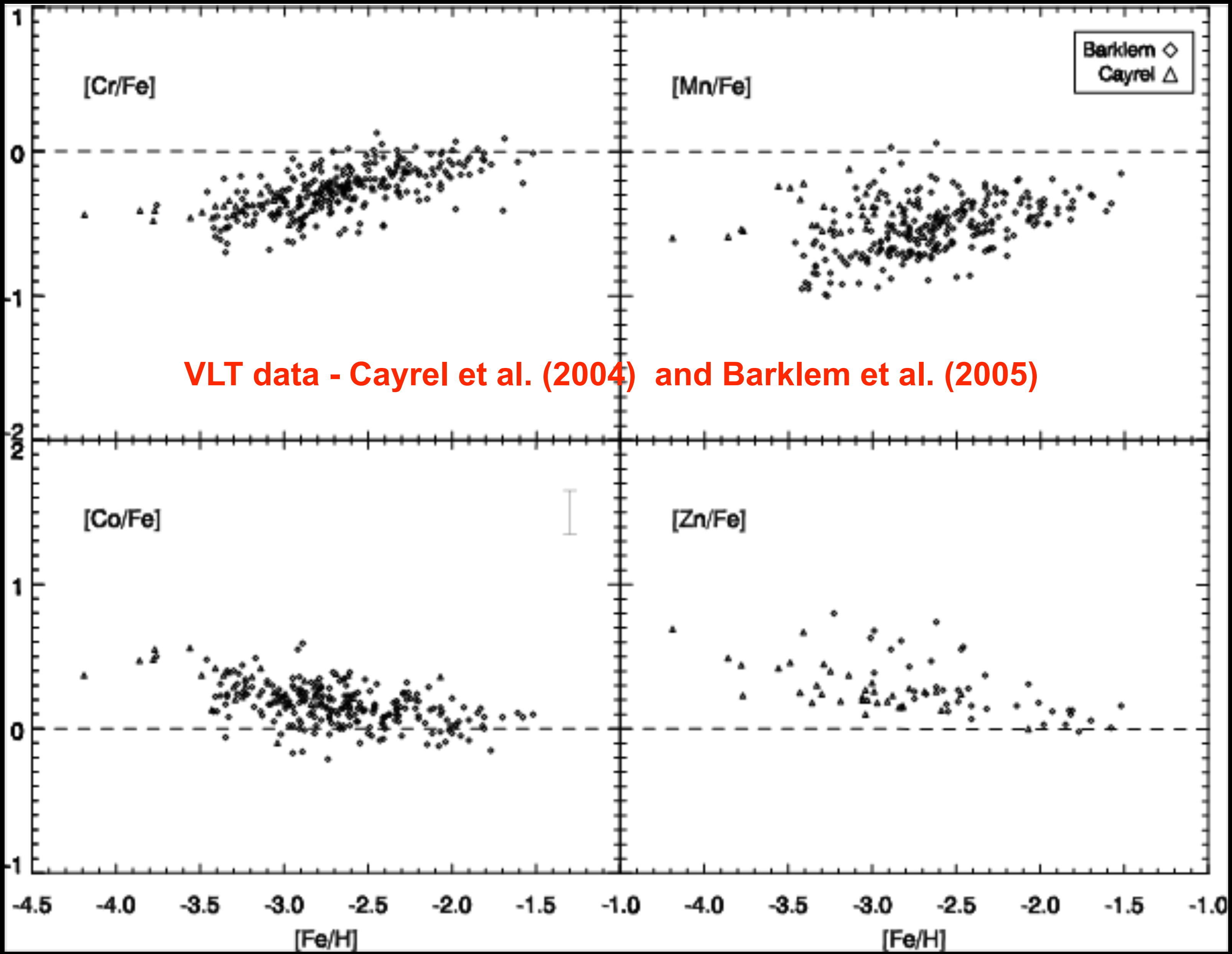
Illustration Case Studies Weigh Progress and Ignorance

What have we already done to extract info from the fossil record, and what are its limitations?



Case Study 1: r-process, iron peak and the first stars



Illustration

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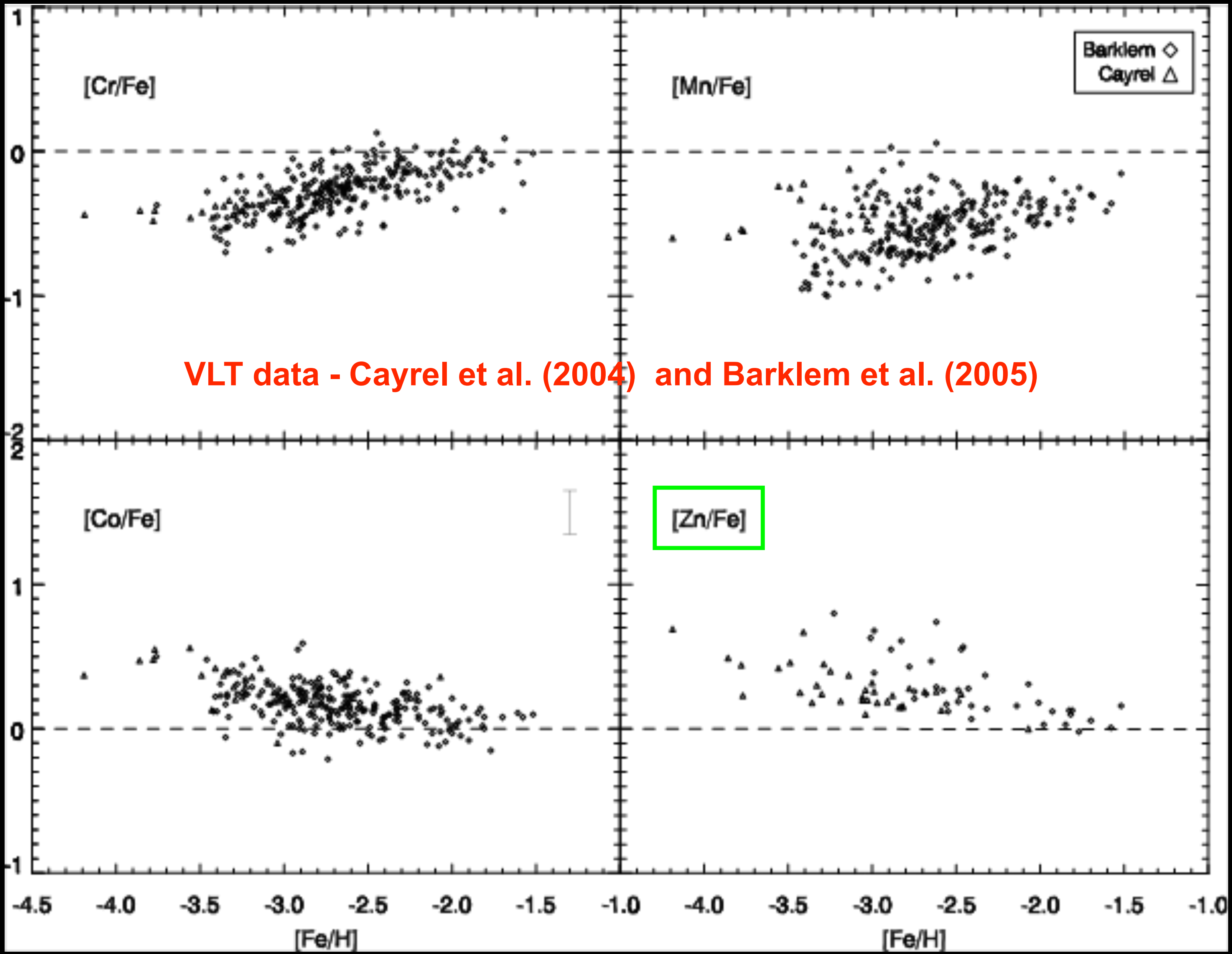

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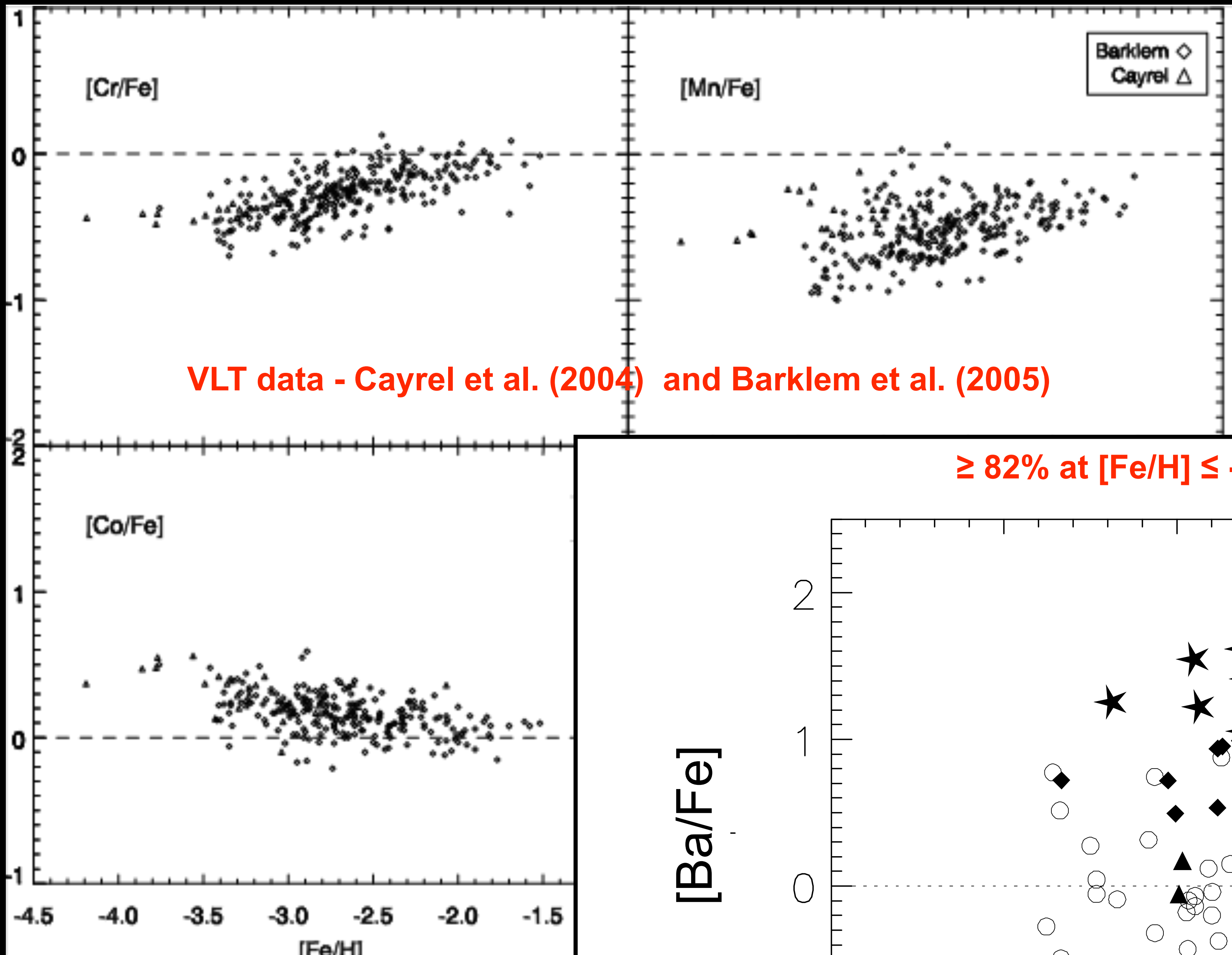
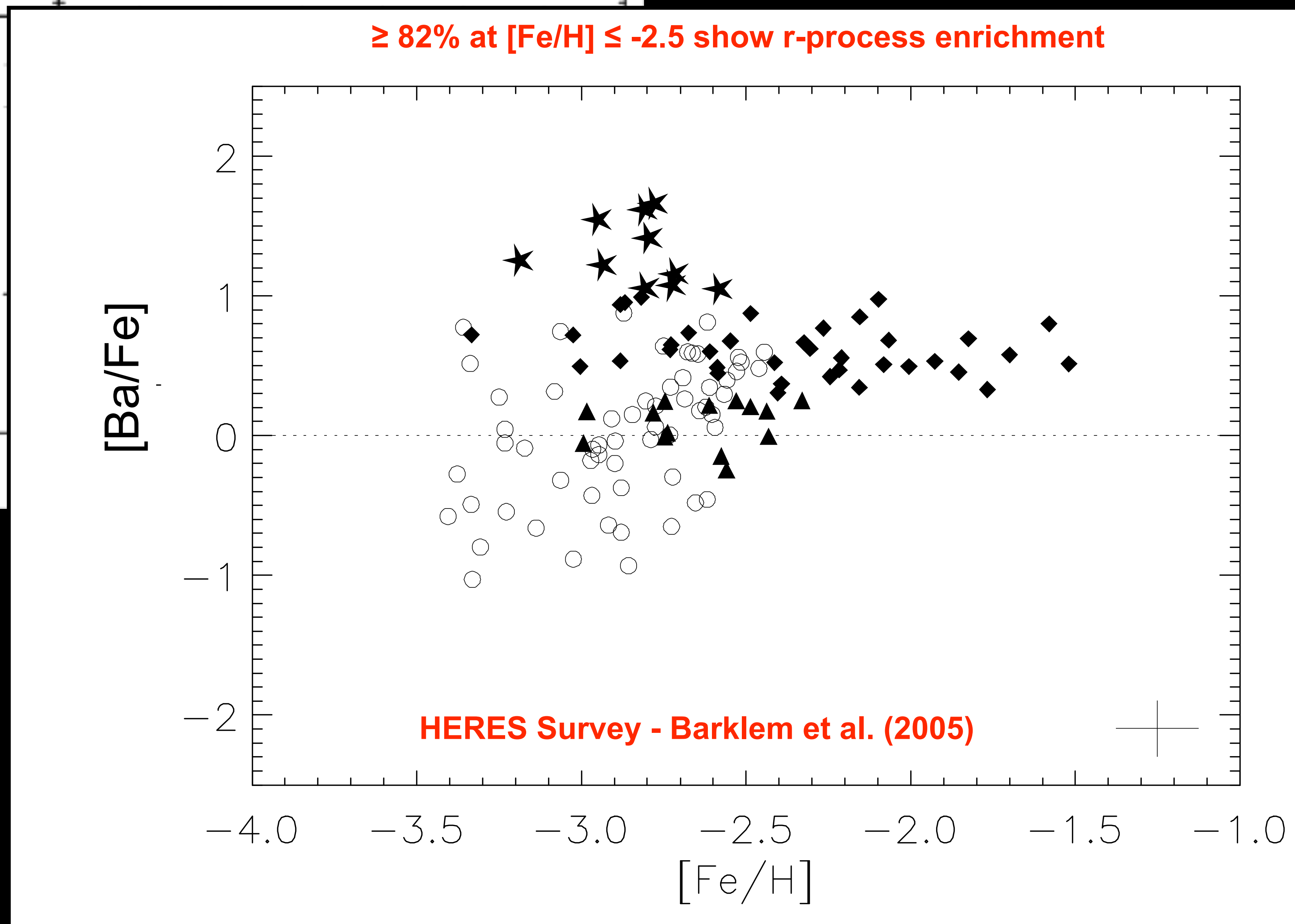
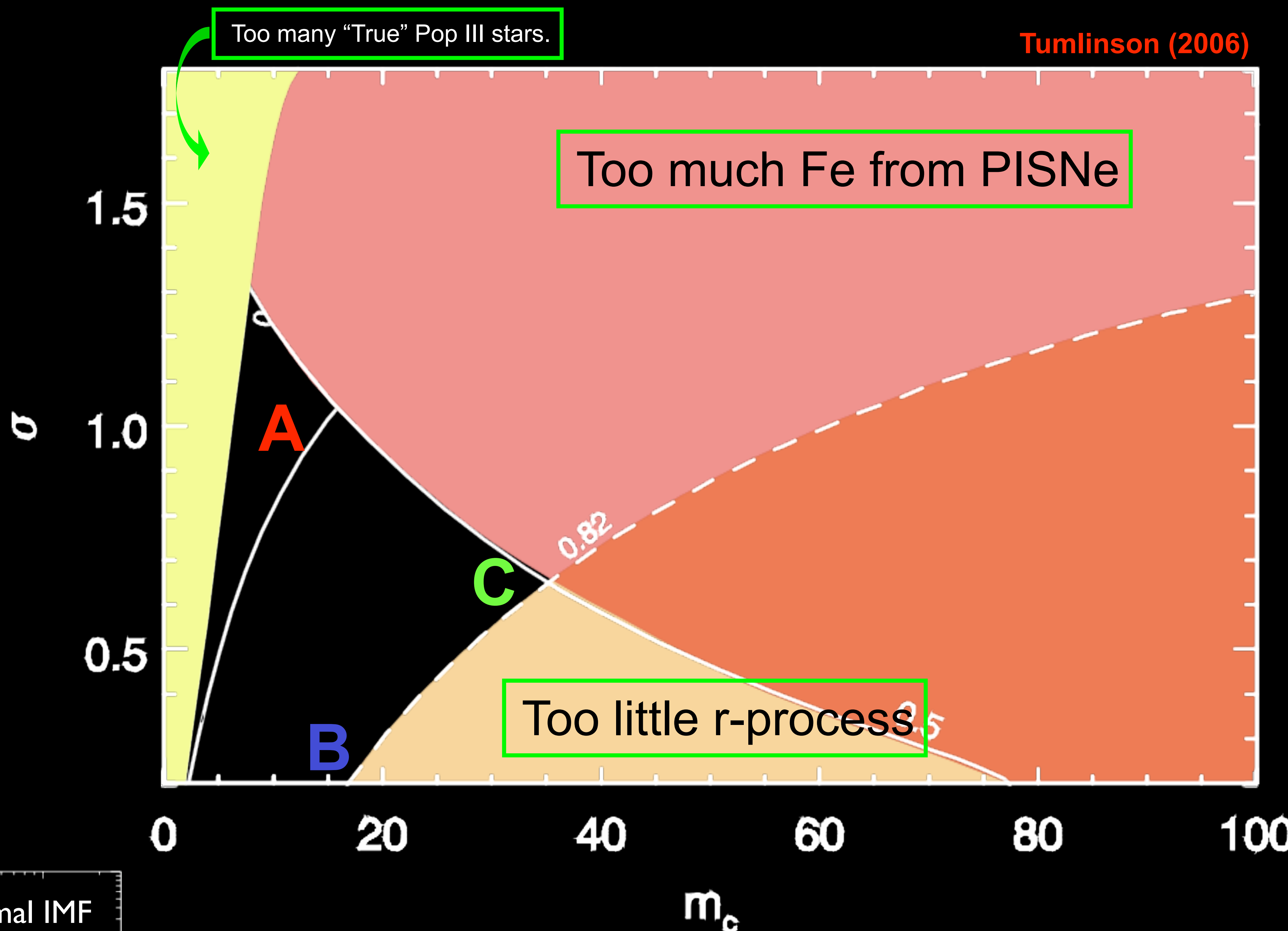
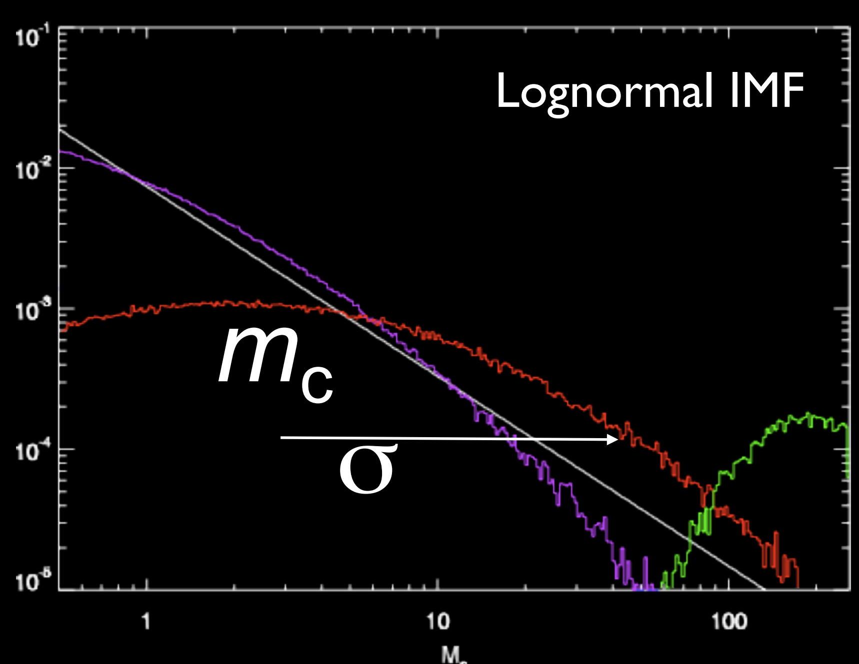




Illustration

Illustration

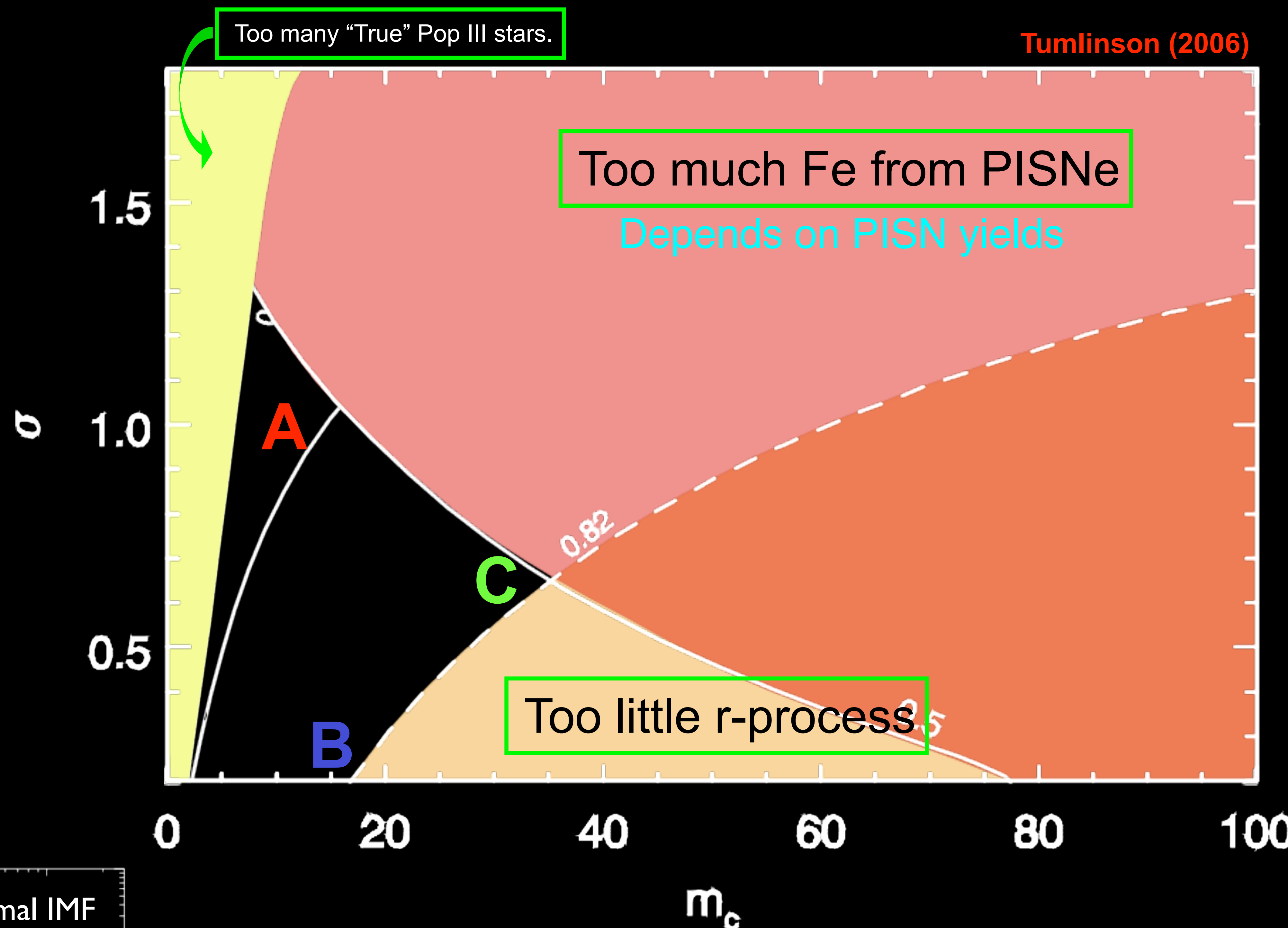


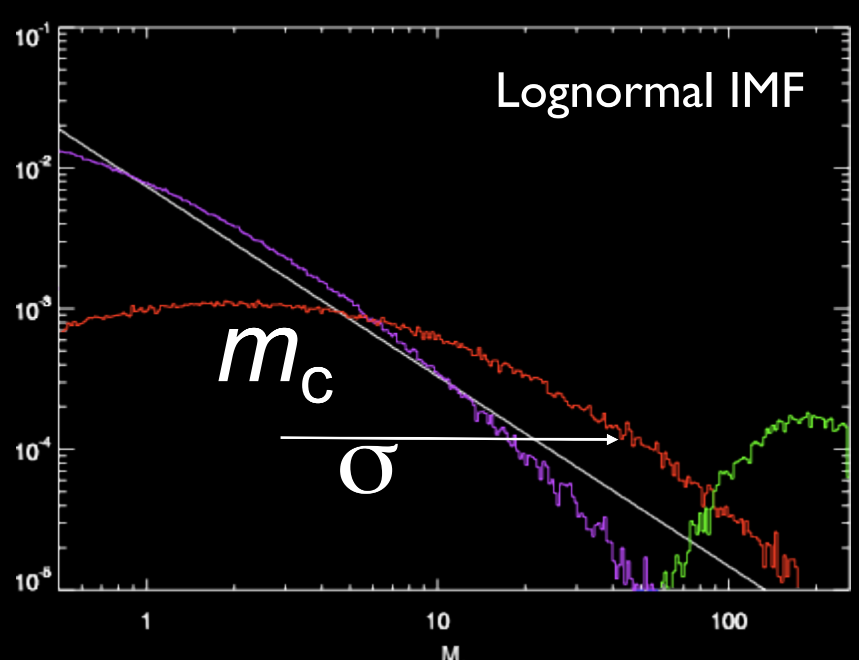


30% Progress: We have shown that these abundances do provide leverage in the interesting mass range.

70% Ignorance: But what are the mass yields really, and how many parameters do the yields have (M, E_{51}, fallback, mixing, phase of moon).

Illustration





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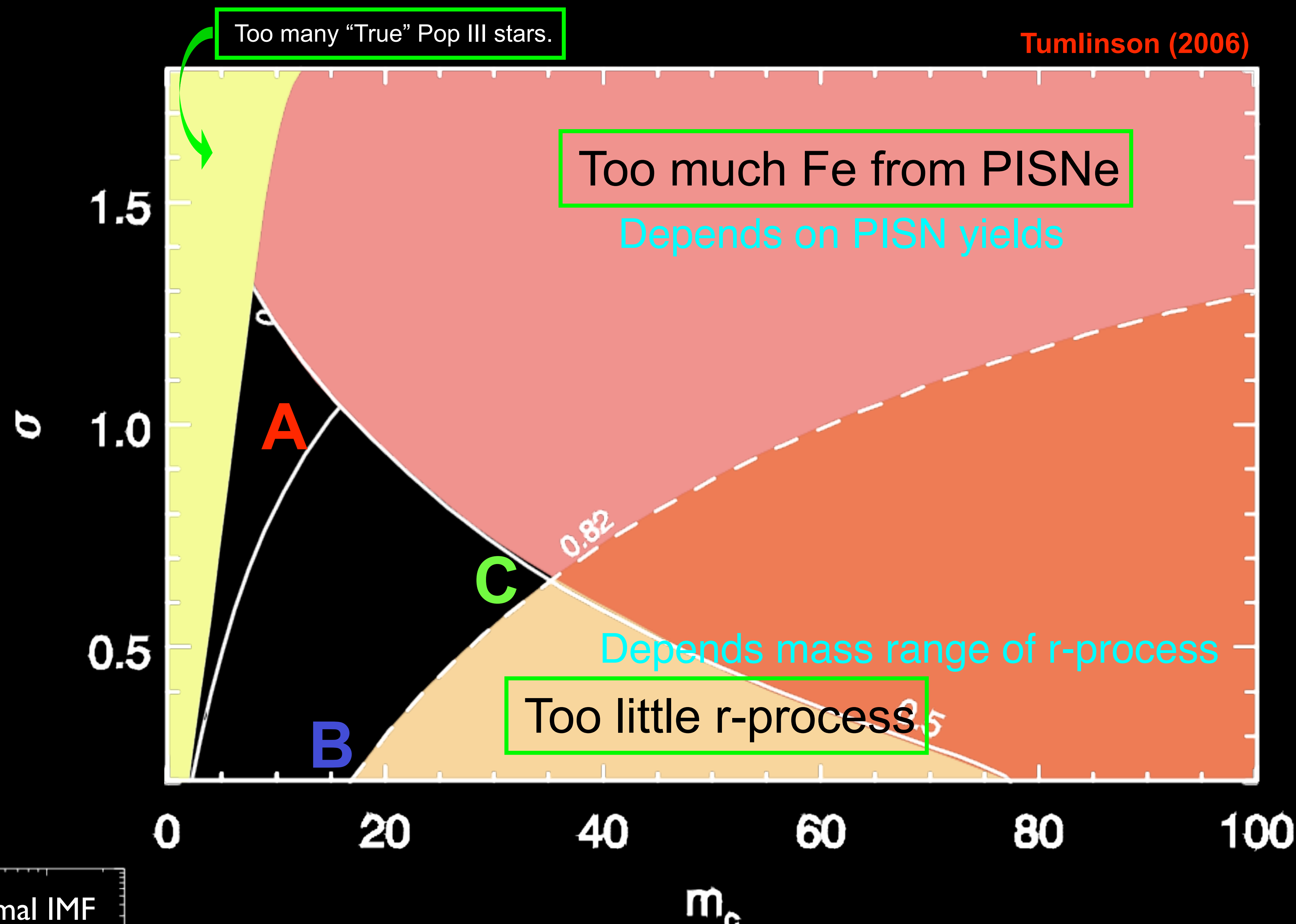

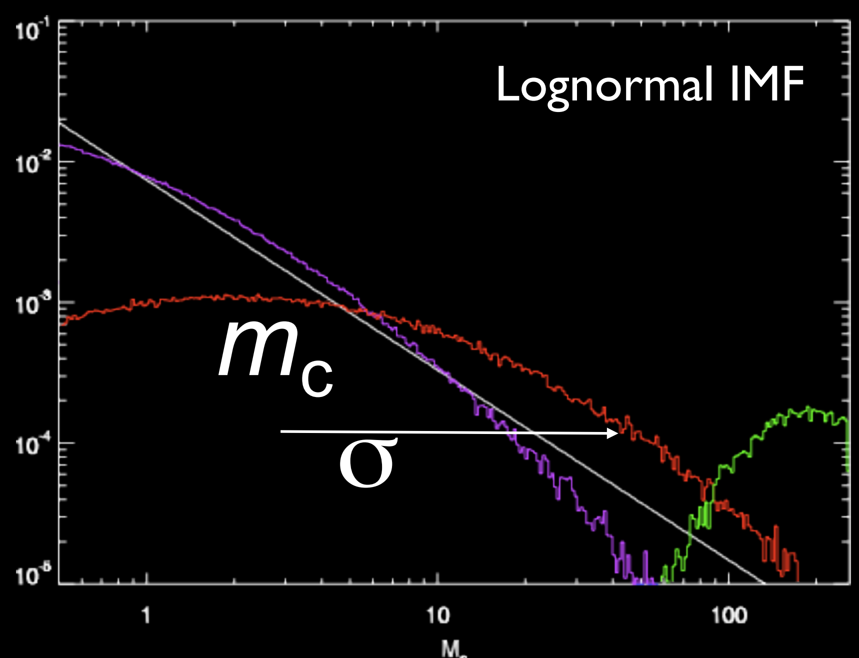

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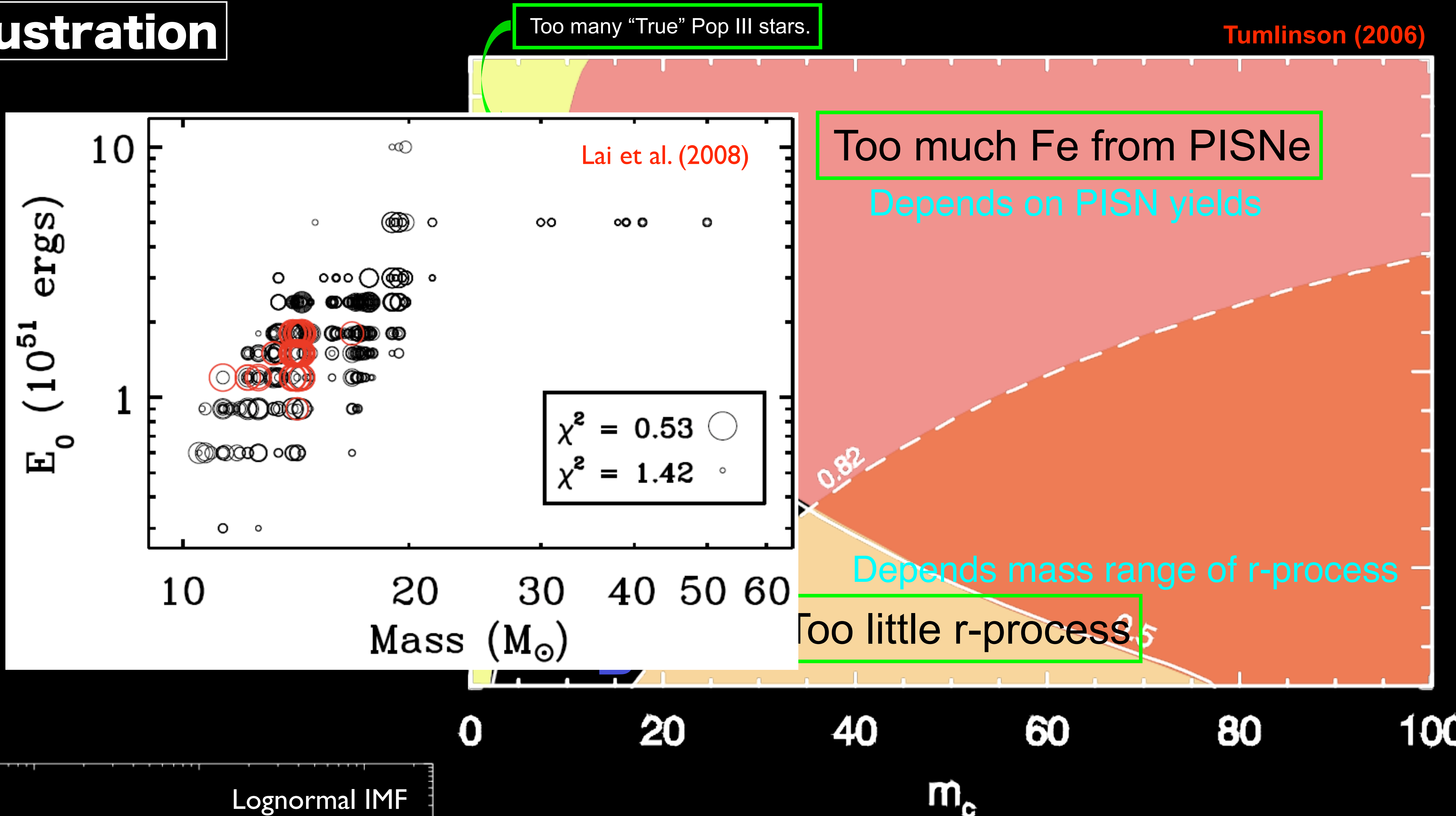

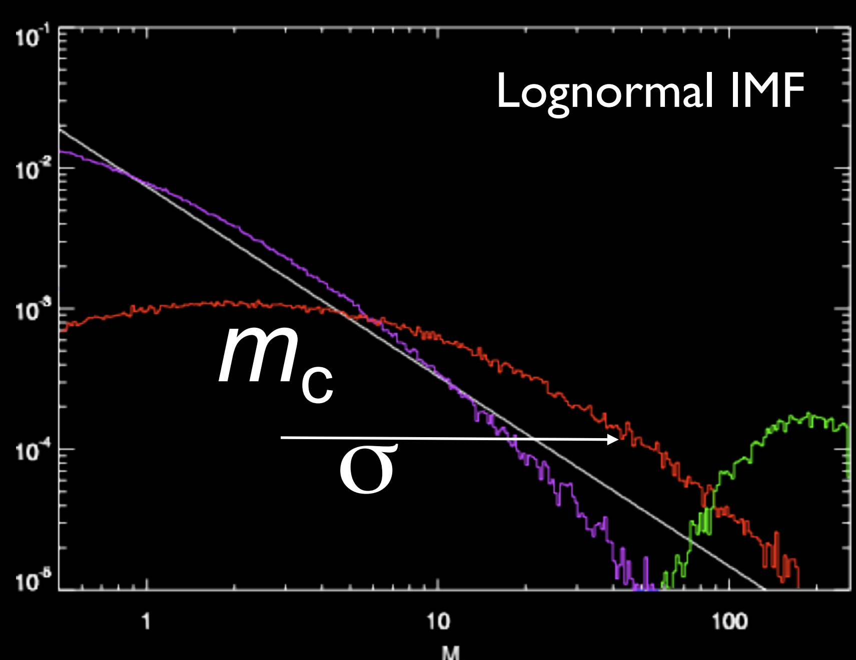

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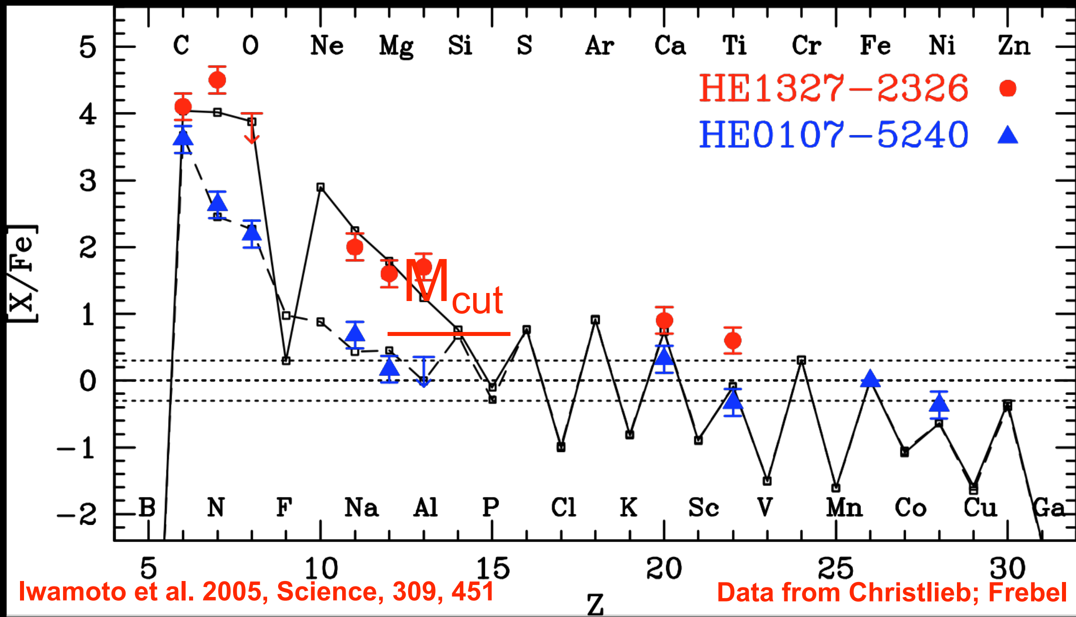
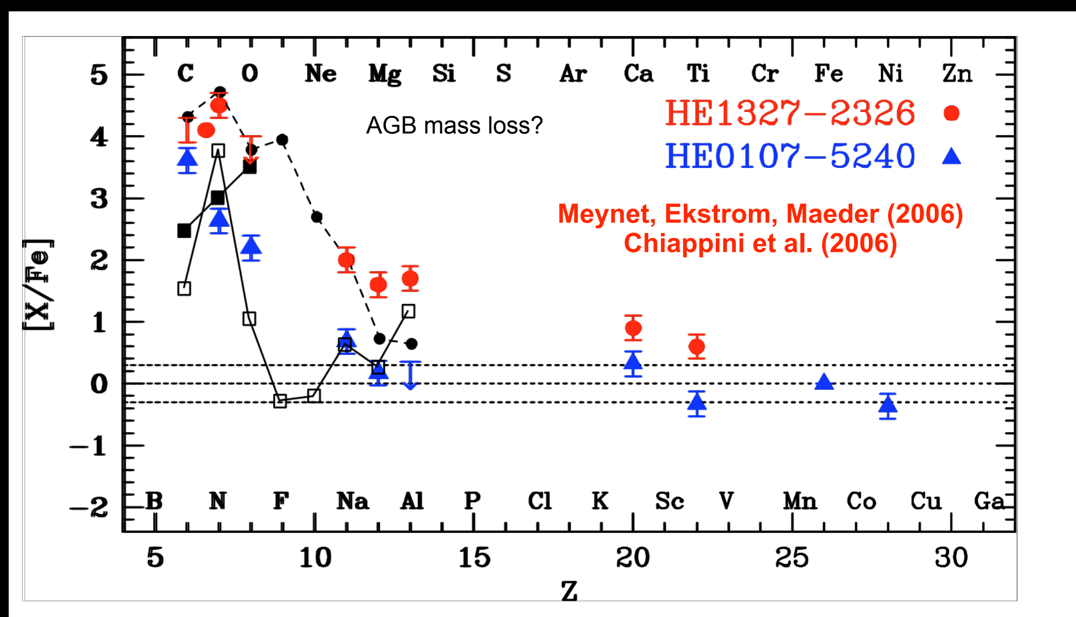
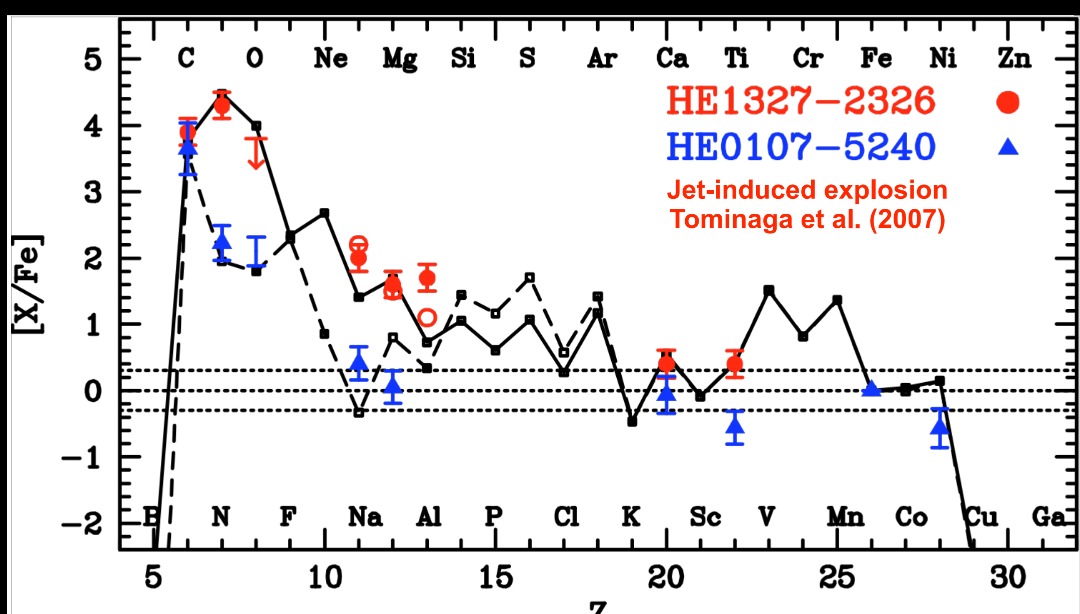


Faint SNe in which light elements escape but heavy elements fall into the black hole? (Iwamoto et al. 2005)



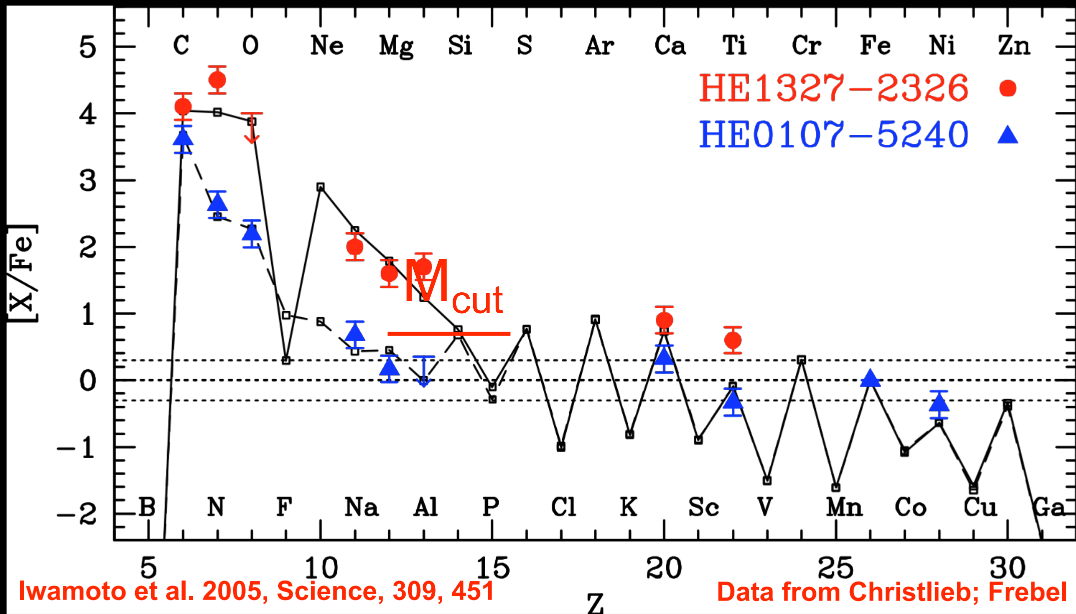
Stellar winds from rapidly rotating Z = 0 stars, or AGB mass loss?



A jet-induced (GRB-like) explosion with mixing and fallback?

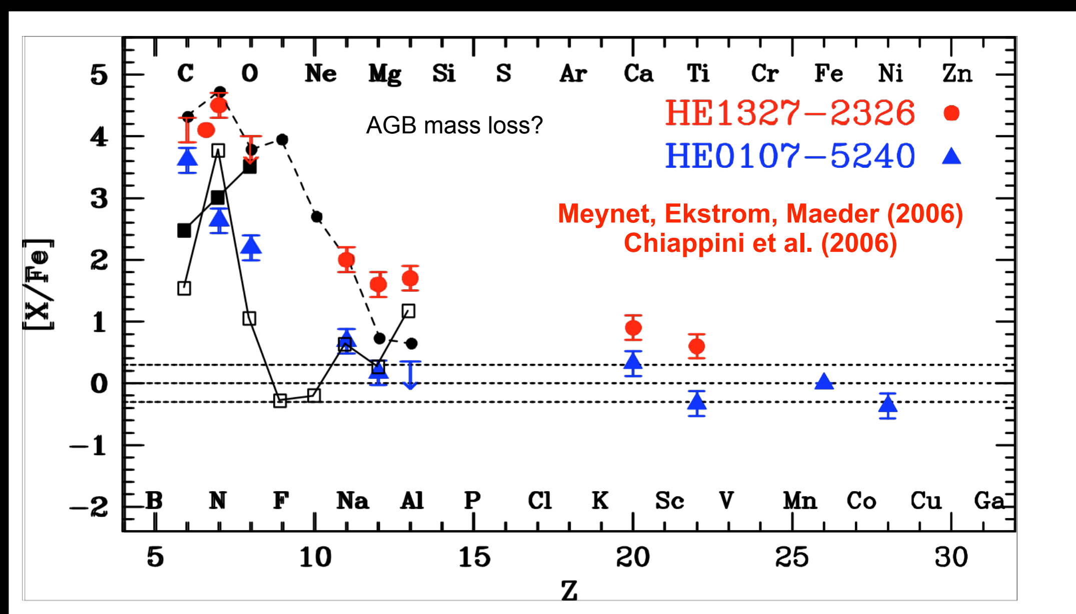
Case Study 2: The origins of the HMP stars

Illustration



Faint SNe in which light elements escape but heavy elements fall into the black hole? (Iwamoto et al. 2005)

20% Progress: We have "existence proofs" for various unusual abundance patterns.



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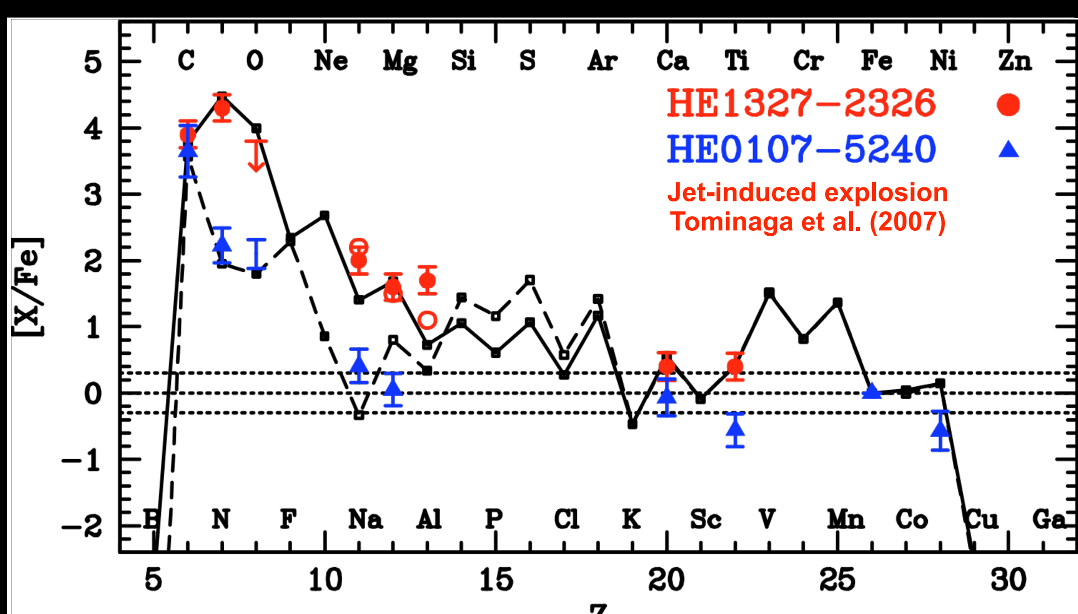

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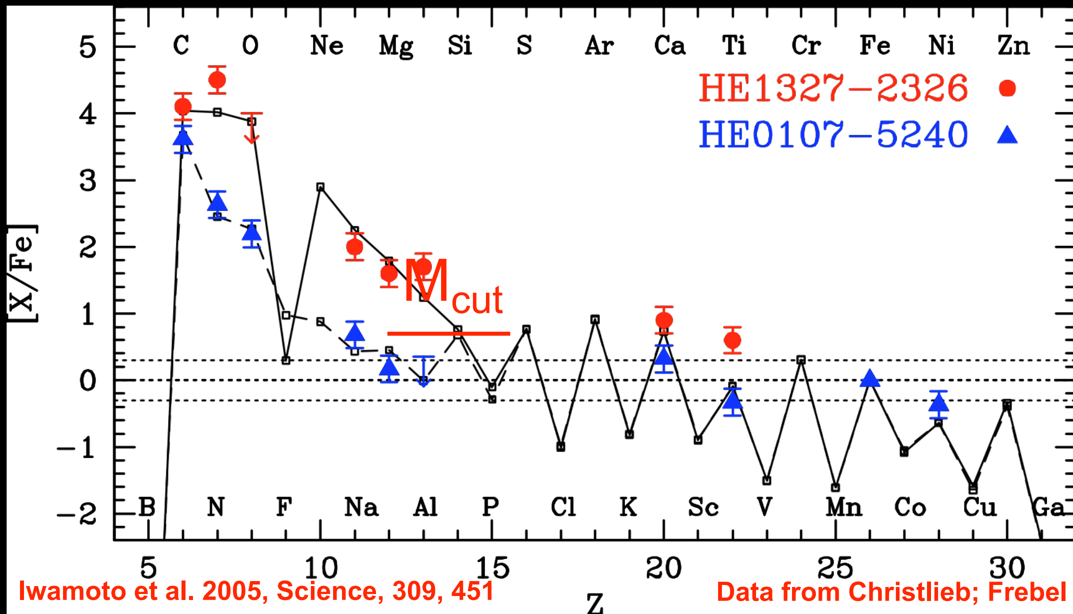
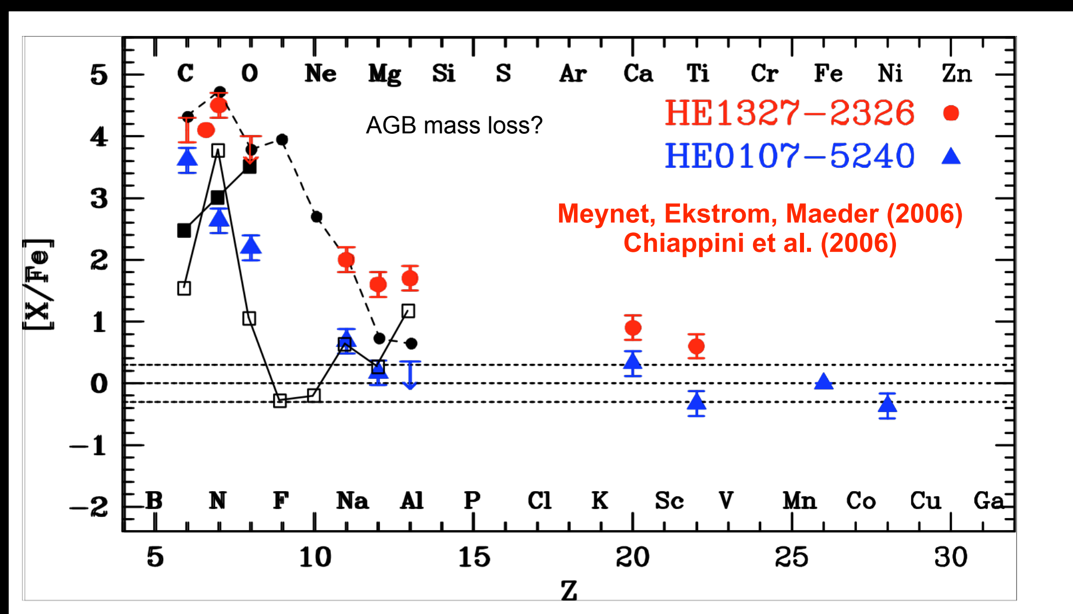
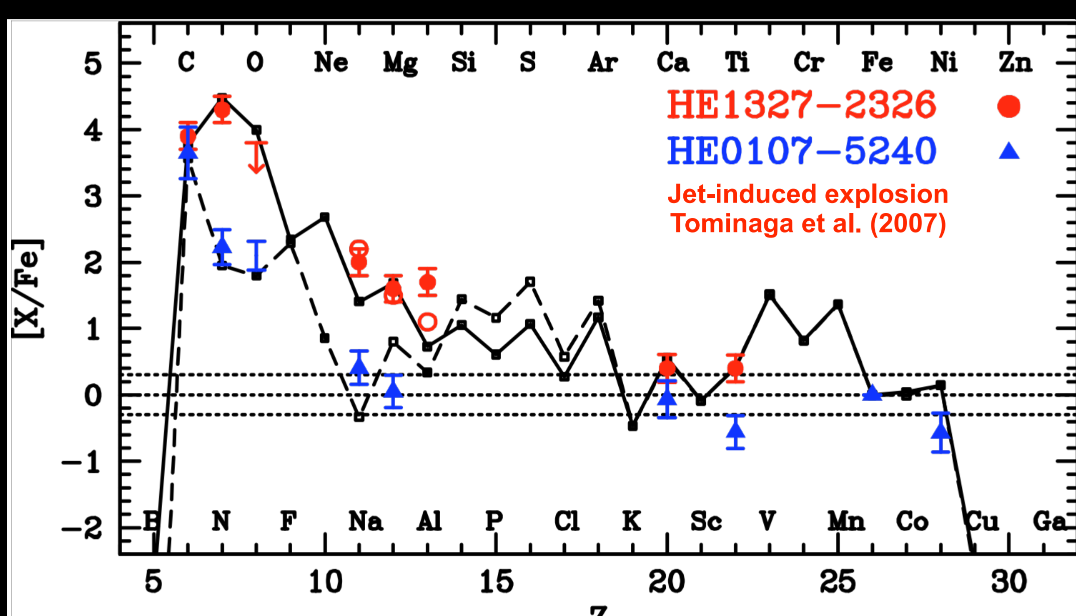
Illustration







Faint SNe in which light elements escape but heavy elements fall into the black hole? (Iwamoto et al. 2005)

20% Progress: We have "existence proofs" for various unusual abundance patterns.

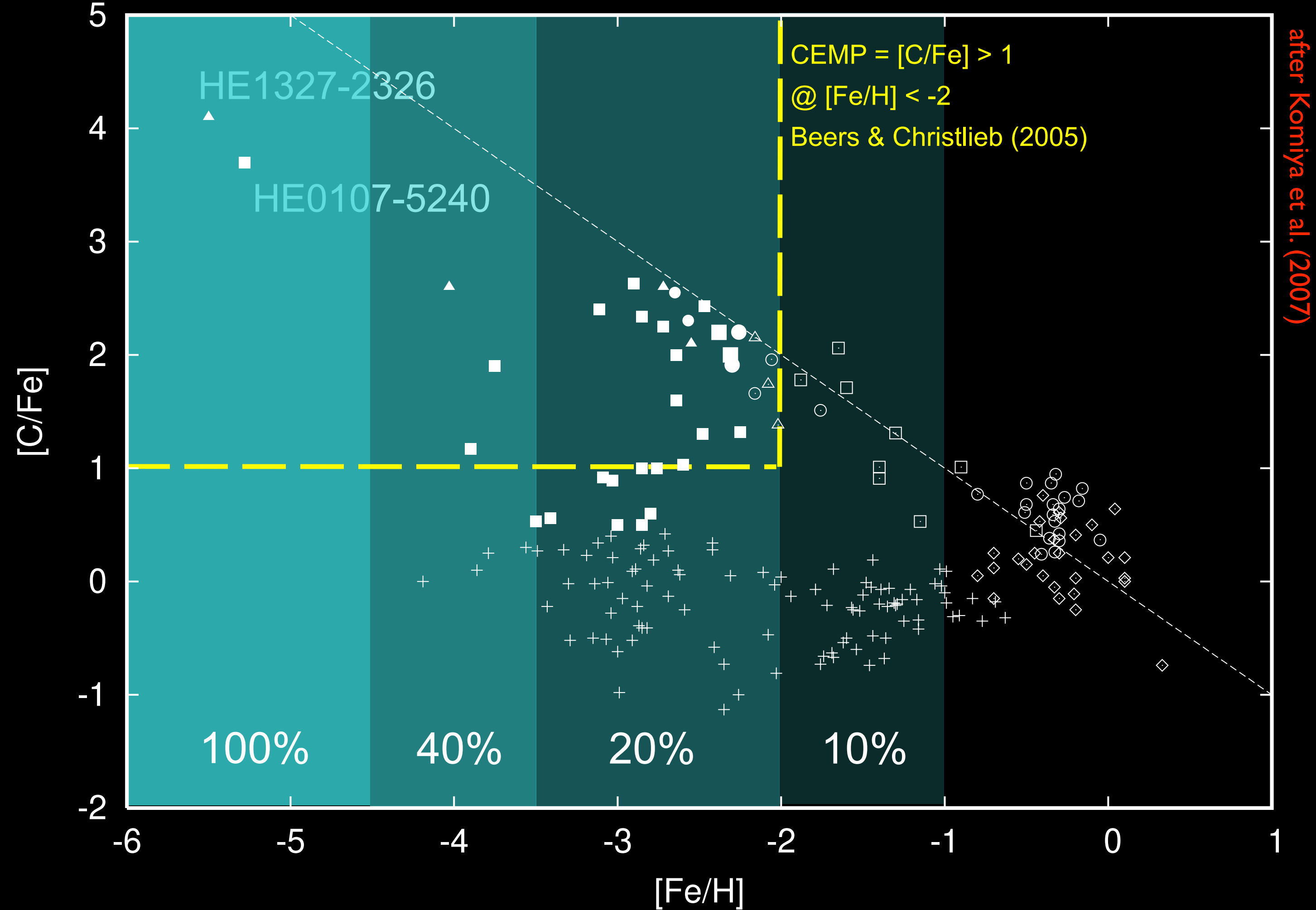
Stellar winds from rapidly rotating Z = 0 stars, or AGB mass loss?

80% Ignorance: But instead of just a few uncertain parameters, we now have many competing mechanisms!

A jet-induced (GRB-like) explosion with mixing and fallback?

Case Study 2: The origins of the HMP stars

Case Study 3: CEMP Zoo and AGB Nucleosynthesis



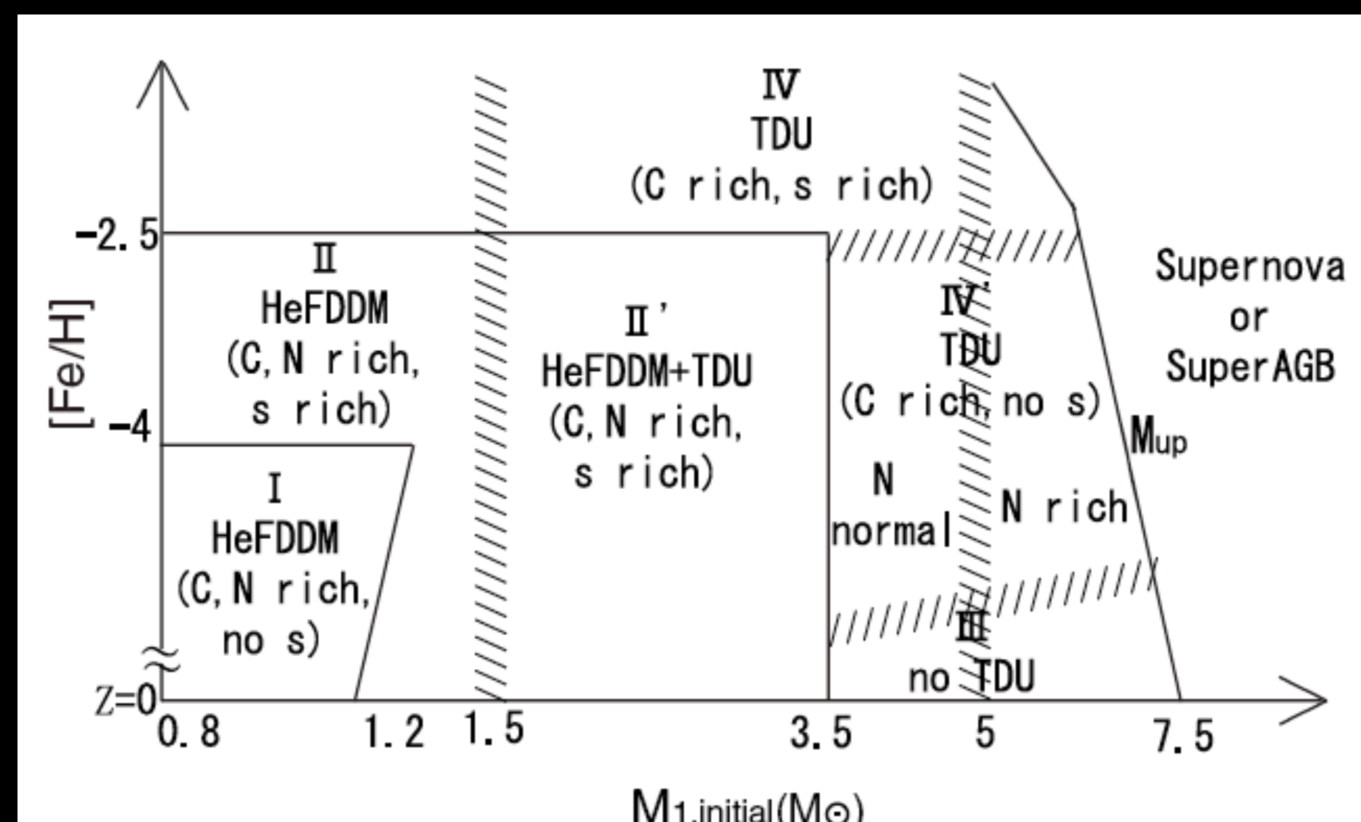
The Carbon-Enhanced Metal-Poor Star Zoo

CEMP
CEMP-no
CEMP-r
CEMP-s
CEMP-r/s

40% Progress

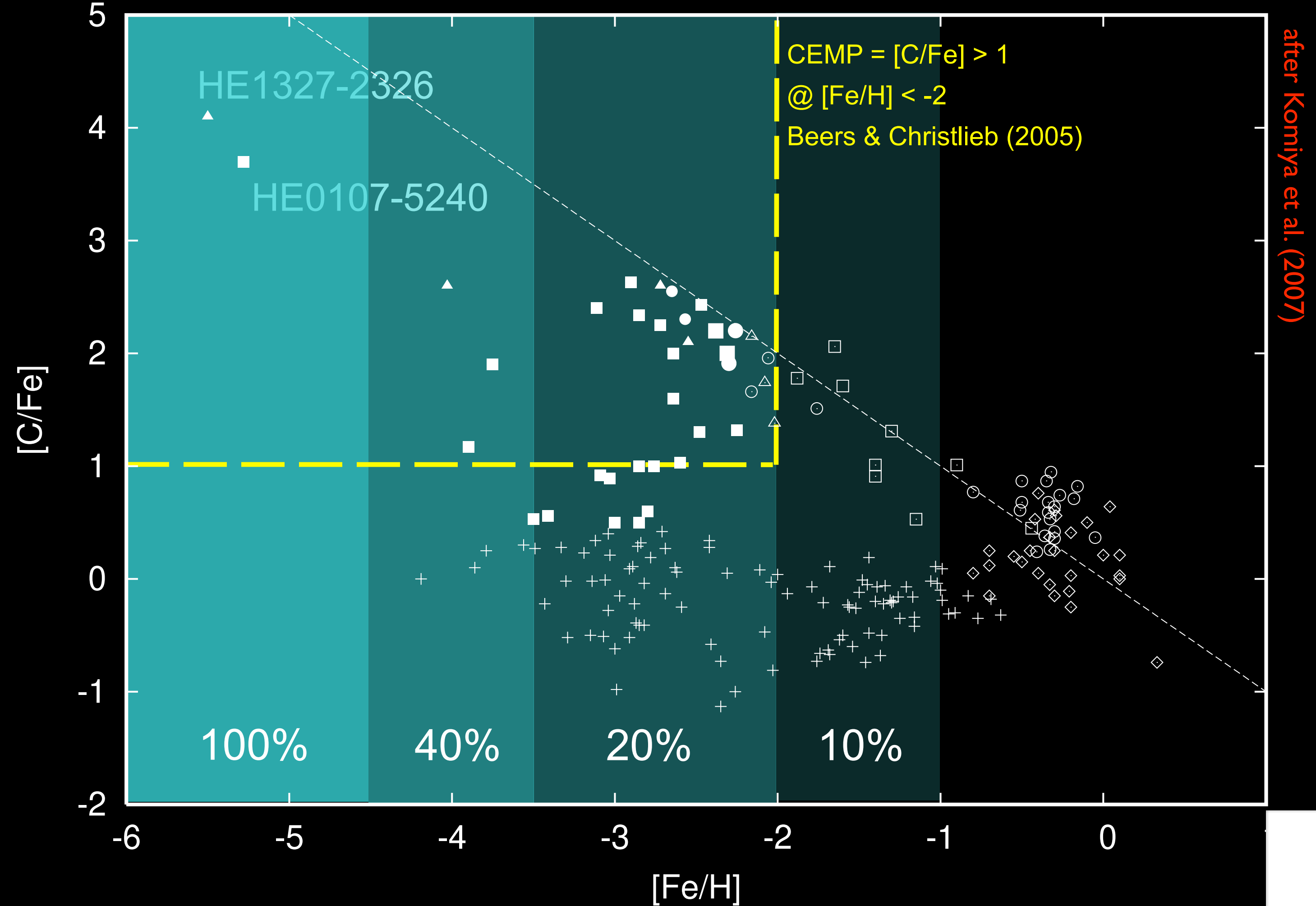
all these phenomena may relate to the mass-and-metallicity dependent yields of intermediate mass stars and AGB (Suda et al. 2006, Komiya et al. 2007, Masseron et al. 2009)

60% Ignorance



Illustration

Case Study 3: CEMP Zoo and AGB Nucleosynthesis



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40% Progress

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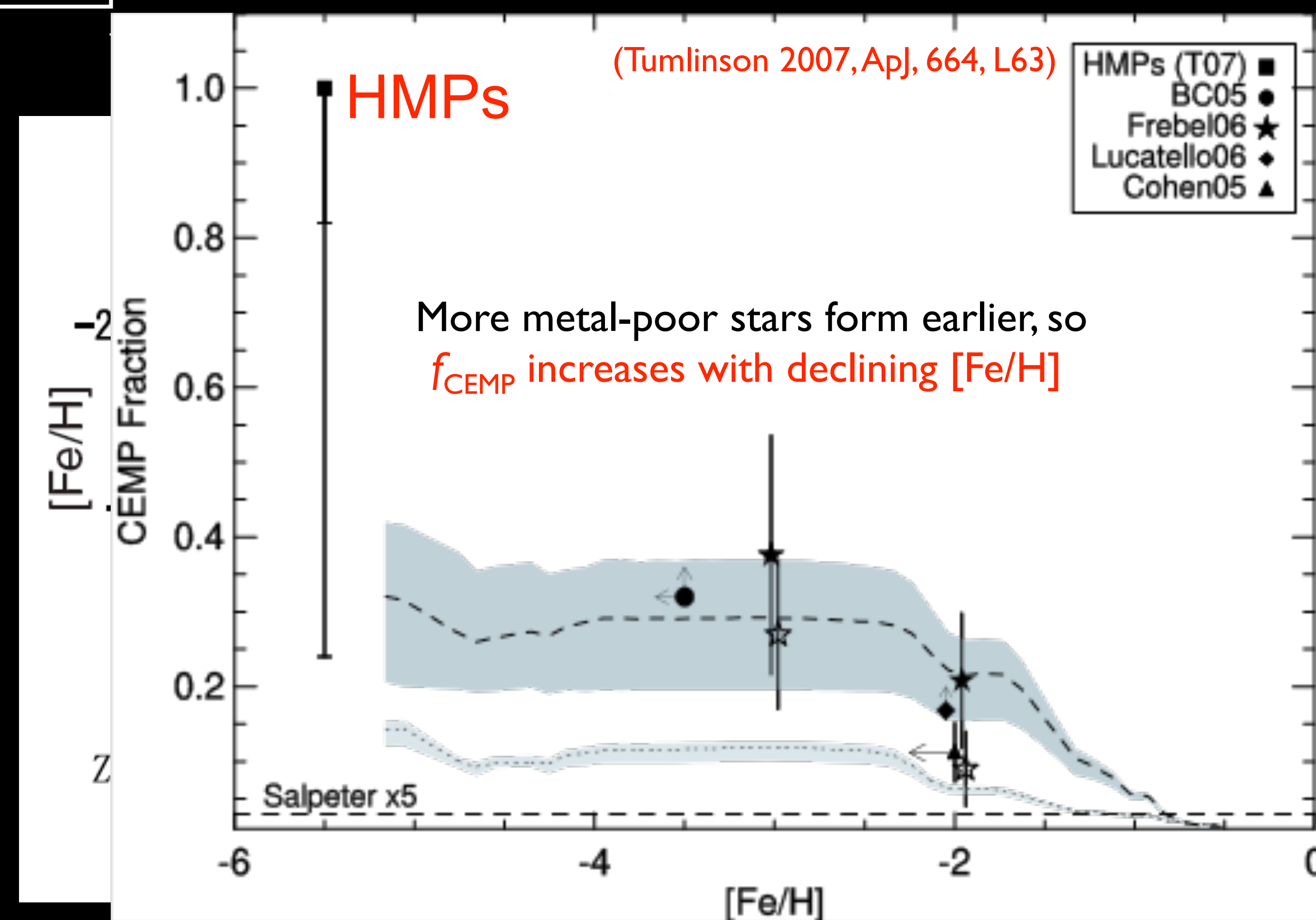
60% Ignorance

A top heavy IMF is indicated (Lucatello et al. 2005; Komiya et al. 2007, Tumlinson 2007a,b) but depends on yields. How can these be independently tested?

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

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



Illustration

Case Study 1:

We can constrain the primordial IMF using r-process and iron-peak elements, but we need to know the yields of these elements as a function of mass, etc.

Case Study 2:

We can reproduce the abundance patterns seen in the "HMP Stars", with too many non-unique and poorly understood mechanisms.

Case Study 3:

We can make CEMP stars with AGB mass transfer, but we can't make every animal in the zoo in the correct proportions. Implications for IMF depend on it.

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Case Study 3:

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The Score: About 20% progress, and 80% ignorance.

We have now . . .

We have now . . .

. . . motivated our search of the fossil record

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. . . motivated our search of the fossil record

. . . educated ourselves about the state of the art

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It’s time for some:

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So what do we do now?

It's time for some:

Imagination

Elements of a Good Chemical Evolution Model

It must be:

1) Hierarchical, because that's how the early Galaxy formed.

2) Stochastic, because that's how early chemical evolution unfolded.

3) Able to generate fully synthetic abundance patterns that look like data in ~12 - 15 elements from all important nucleosynthetic groups (α, Fe, r, s).

4) Based on a self-consistent, homogeneous, well-sampled grid of stellar evolution models and chemical yields.

5) Able to track the mixing and dispersal of chemical elements.
(Whether accurately or not, and also stochastically).

6) Able to perform statistical comparisons against data and adjust itself for optimal fits.

7) Able to provide unique answers to questions of star formation history and IMF.

Concrete Steps to Move the Ball on Three Fronts

1) Unification of semi-analytic and numerical modeling.

2) Ever-improving yields and mapping to initial mass.

3) Leveraging related community initiatives.

1) Unifying SAM and Numerical Models

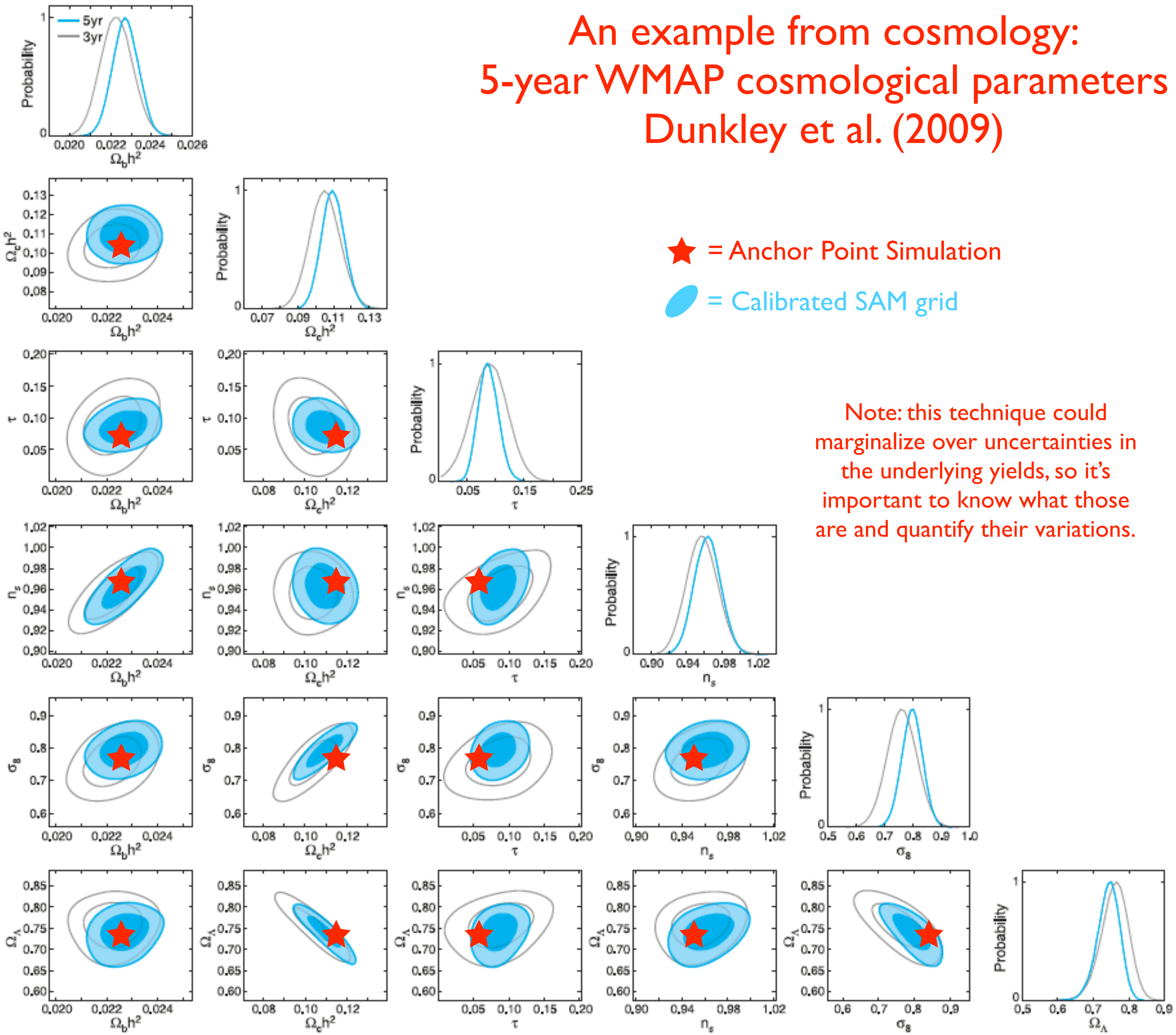
Numerical simulations will gradually get better and more detailed, and will advance the frontier, but the state-of-the-art ones will always be expensive by definition.

So SAMs still have a role, since for certain applications they can be calculated "on the fly", and used to supply realistic stellar populations for much higher resolution Nbody simulations.

Next important step: implement a homogeneous set of yields identically in both SAMs and hydrosims, then use sims to run "anchor point" simulations and SAMs to explore parameter space.

Imagination

An example from cosmology: 5-year WMAP cosmological parameters Dunkley et al. (2009)

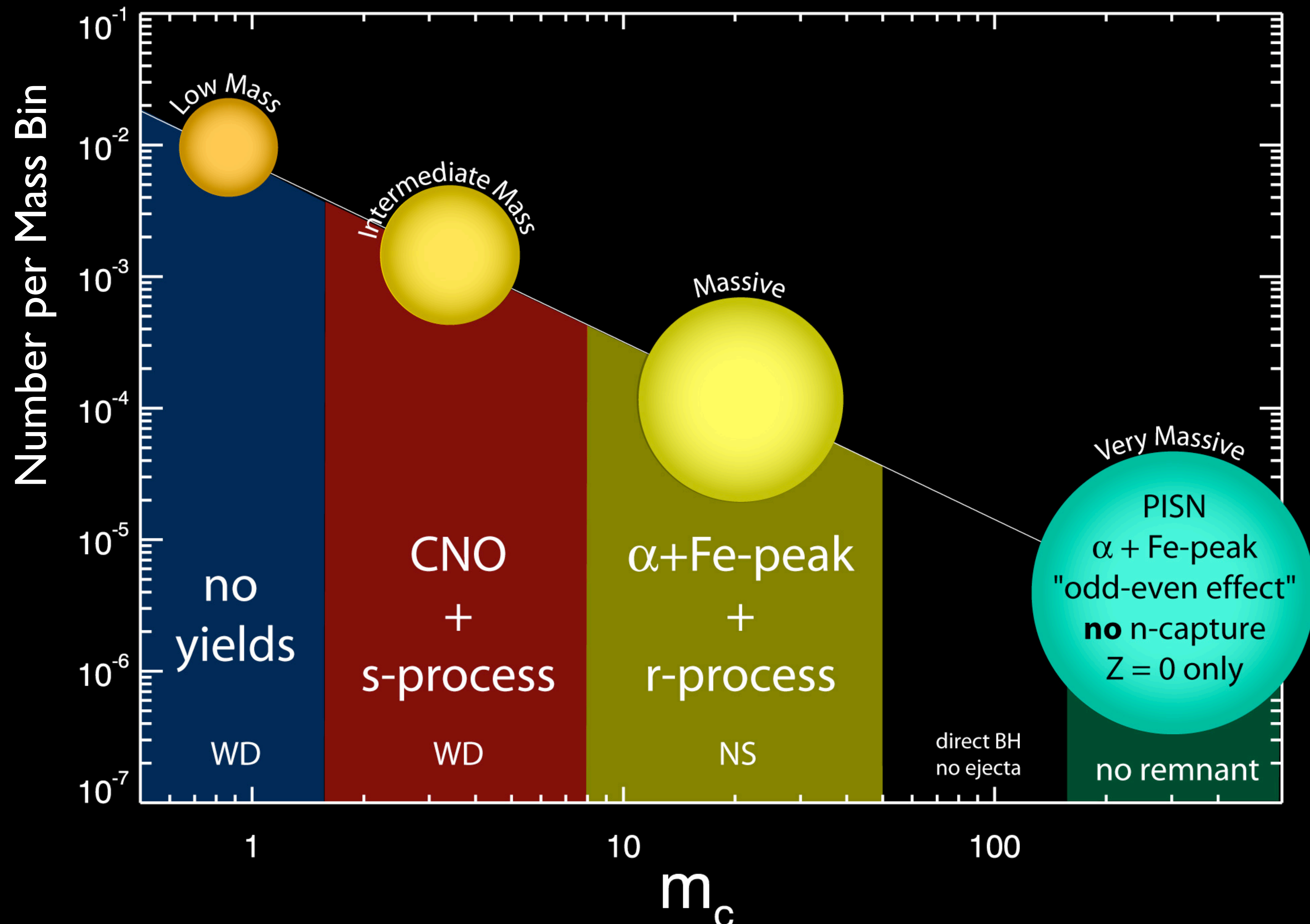


★ = Anchor Point Simulation

= Calibrated SAM grid

Note: this technique could marginalize over uncertainties in the underlying yields, so it's important to know what those are and quantify their variations.

We would like to use robust and distinct signatures of stellar mass to diagnose IMF.



But IMF diagnostics are only as good as the yields on which they are based.

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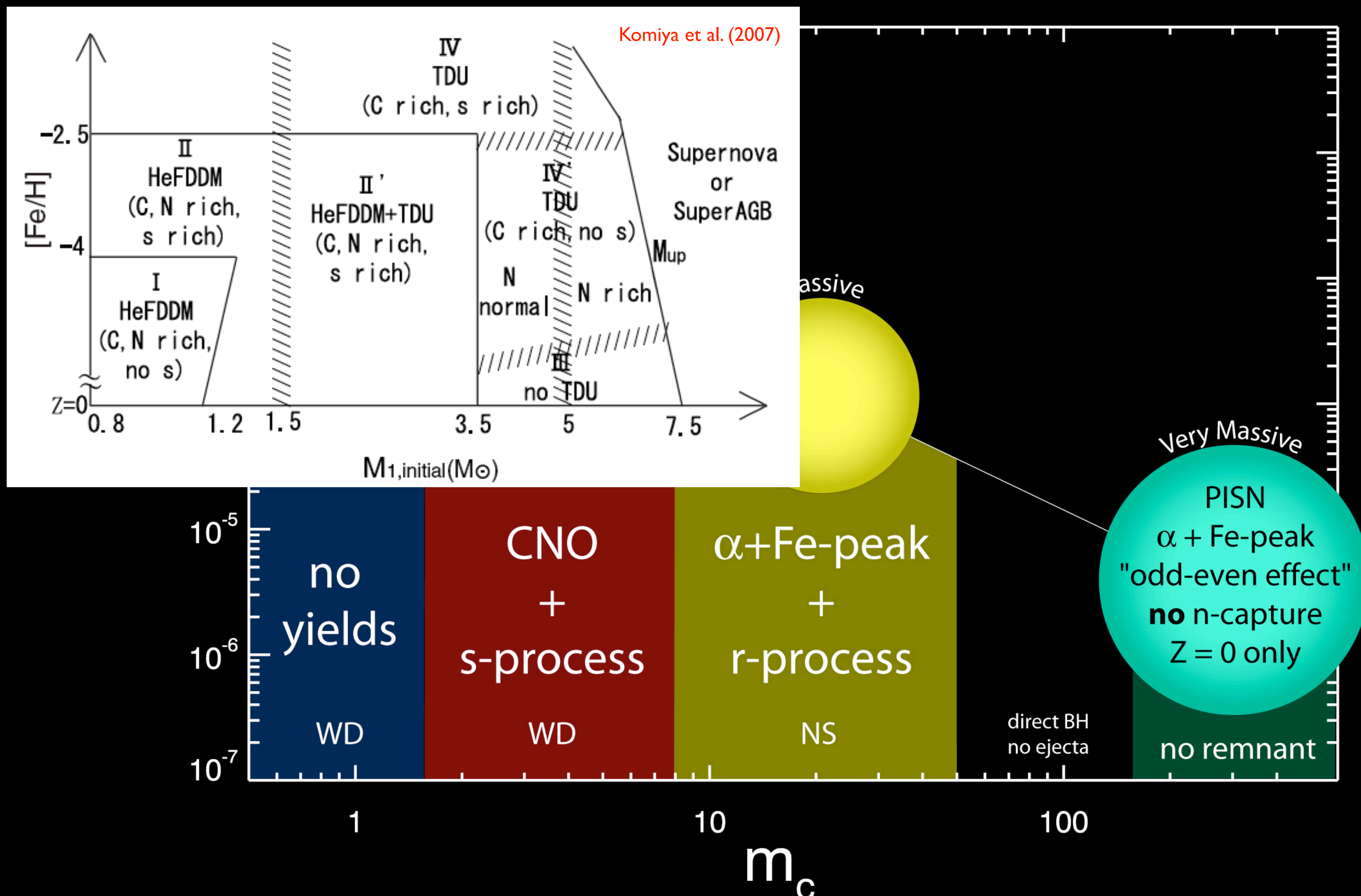

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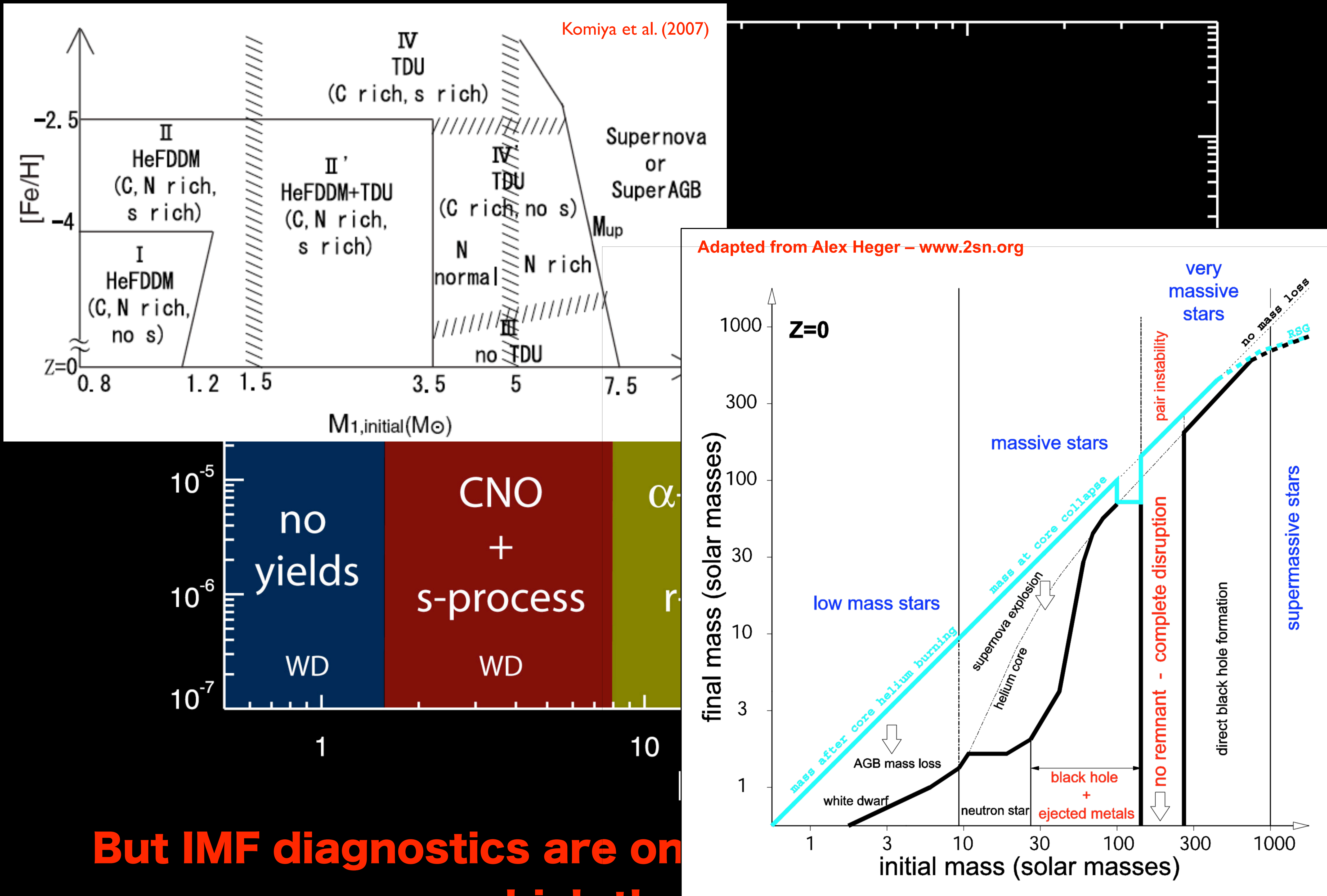

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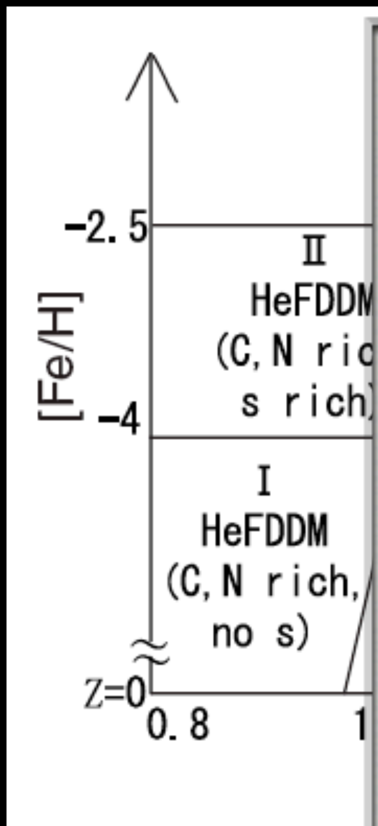
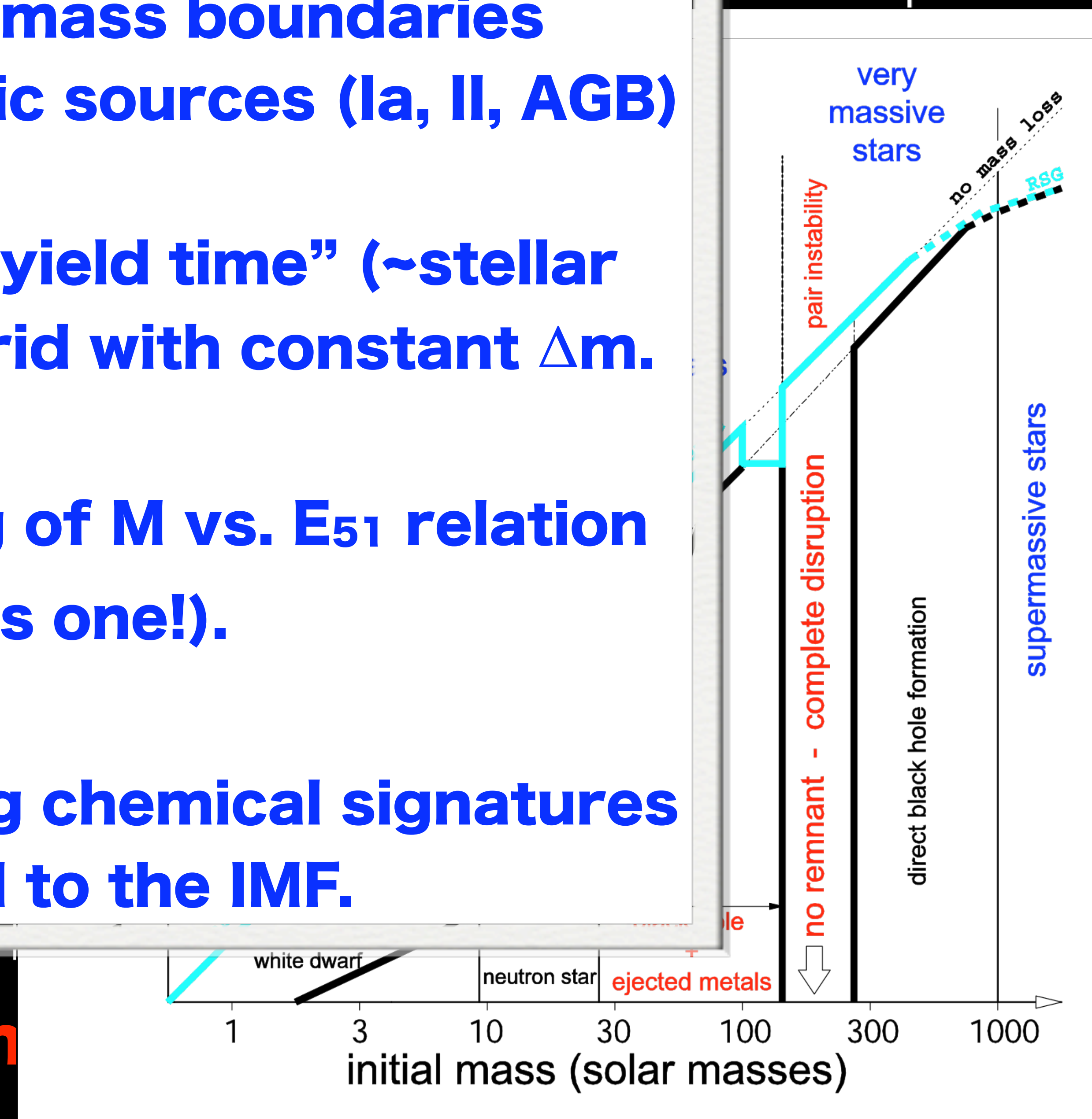


Other specific needs from nuclear physics / stellar evolution

- close attention to mass boundaries between nucleosynthetic sources (Ia, II, AGB)
- models in terms of "yield time" (~stellar lifetime) rather than grid with constant Δm.
- better understanding of M vs. E_{51} relation (if there is one!).
- test mechanisms using chemical signatures that are blind to the IMF.



But IMF diagnostics are on
which they are based.

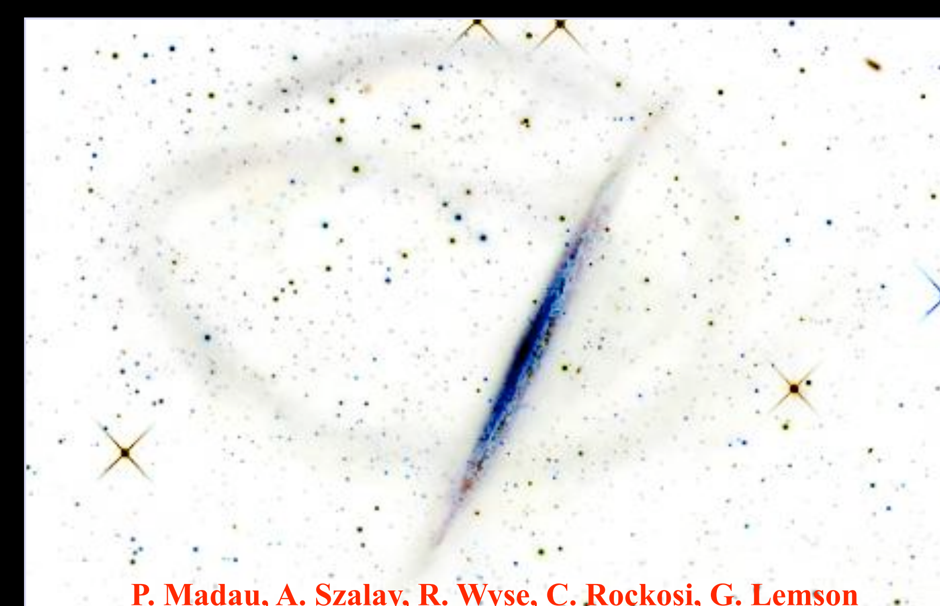
3) Leveraging Related Community Efforts

<u>The Virtual Astronomical Observatory (VAO):</u>

- software that conforms to internationally defined standards and interfaces that allow astronomers to find, retrieve, analyze, integrate, and understand data from telescopes and theoretical simulations around the world.
- funded for $27.5M over 5 years (75% NSF, 25% NASA)
- interested in collaborations with the research community to support data-intensive studies.
- able to supply infrastructure for integration of relevant observational data and theoretical simulations, in exchange for advice on science requirements and feedback.

<u>The Milky Way Laboratory (MWL, SantaCruz + Johns Hopkins):</u>

- a pending NSF Proposal to use cosmology simulations as an immersive laboratory for general users
- use Via Lactea-II (20TB) as prototype, then Silver River (500TB+) as production (15M CPU hours, 10K high-res snapshots)
- Users insert test particles (dwarf galaxies) into system and follow trajectories in pre-computed simulation
- Realistic “streams” from tidal disruption
- Users interact remotely with 0.5PB in ‘real time’



This material is courtesy of VAO Director Bob Hanisch (STScI) and Alex Szalay (JHU).

There is something to be said for just getting people talking.

Though, with the "First Stars" series, last month's Austin First Galaxies Conference, Nuclei in the Cosmos, and others, "just another meeting" won't help.

Any further workshops need to be targeted and organized to be effective.

Parting Thoughts and Issues for Discussion

Just as
nuclear physics,
stellar astronomy,
cosmic structure formation,
and chemical evolution
are themselves major research efforts. . .

. . . How to integrate and synthesize them is itself a research problem. I know because I have tried this for 5 years and not made as much progress as I would like!

This is the problem to which we should address ourselves.

Why?

We are not likely to get at the first stars any other way.