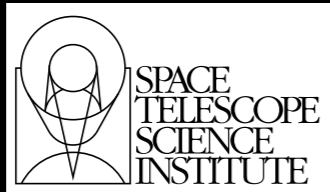


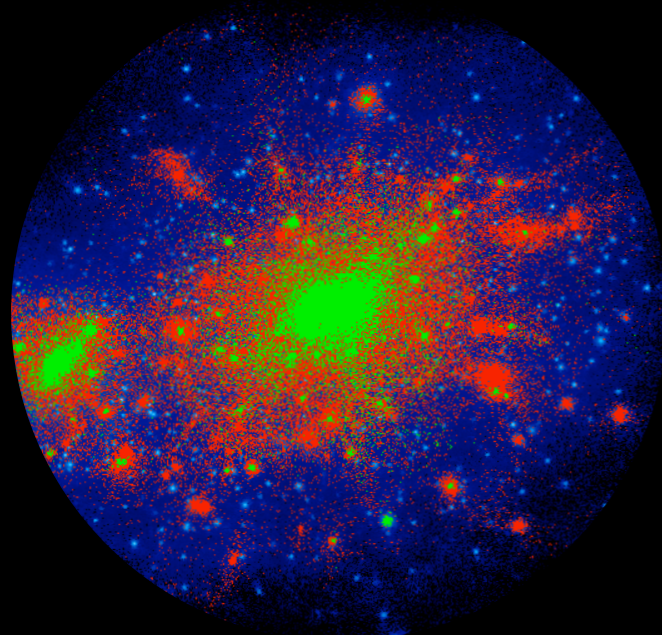
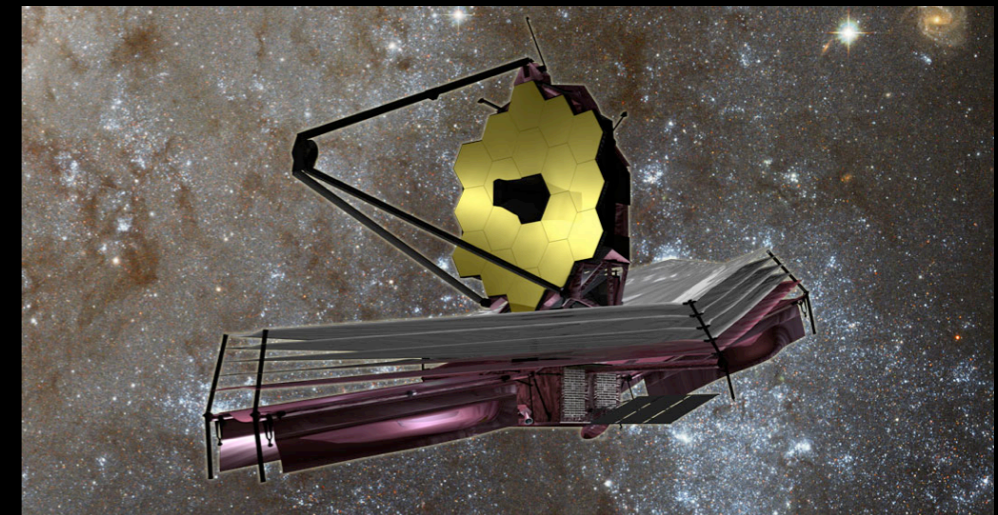
The First Galaxies and the Fossil Record: Challenges for the Next Decade

Jason Tumlinson



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.

A detailed spectral line chart showing various absorption lines. The chart is organized by element and wavelength, with labels such as H1, H2, He1, He2, Li1, Li2, Be1, Be2, B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, B11, B12, B13, B14, B15, B16, B17, B18, B19, C1, C2, C3, C4, C5, C6, C7, C8, C9, C10, C11, C12, C13, C14, C15, C16, C17, C18, C19, C20, C21, C22, C23, C24, C25, C26, C27, C28, C29, C30, C31, C32, C33, C34, C35, C36, C37, C38, C39, C40, C41, C42, C43, C44, C45, C46, C47, C48, C49, C50, C51, C52, C53, C54, C55, C56, C57, C58, C59, C60, C61, C62, C63, C64, C65, C66, C67, C68, C69, C70, C71, C72, C73, C74, C75, C76, C77, C78, C79, C80, C81, C82, C83, C84, C85, C86, C87, C88, C89, C90, C91, C92, C93, C94, C95, C96, C97, C98, C99, C100, C101, C102, C103, C104, C105, C106, C107, C108, C109, C110, C111, C112, C113, C114, C115, C116, C117, C118, C119, C120, C121, C122, C123, C124, C125, C126, C127, C128, C129, C130, C131, C132, C133, C134, C135, C136, C137, C138, C139, C140, C141, C142, C143, C144, C145, C146, C147, C148, C149, C150, C151, C152, 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C983, C984, C985, C986, C987, C988, C989, C990, C991, C992, C993, C994, C995, C996, C997, C998, C999, C1000.

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)

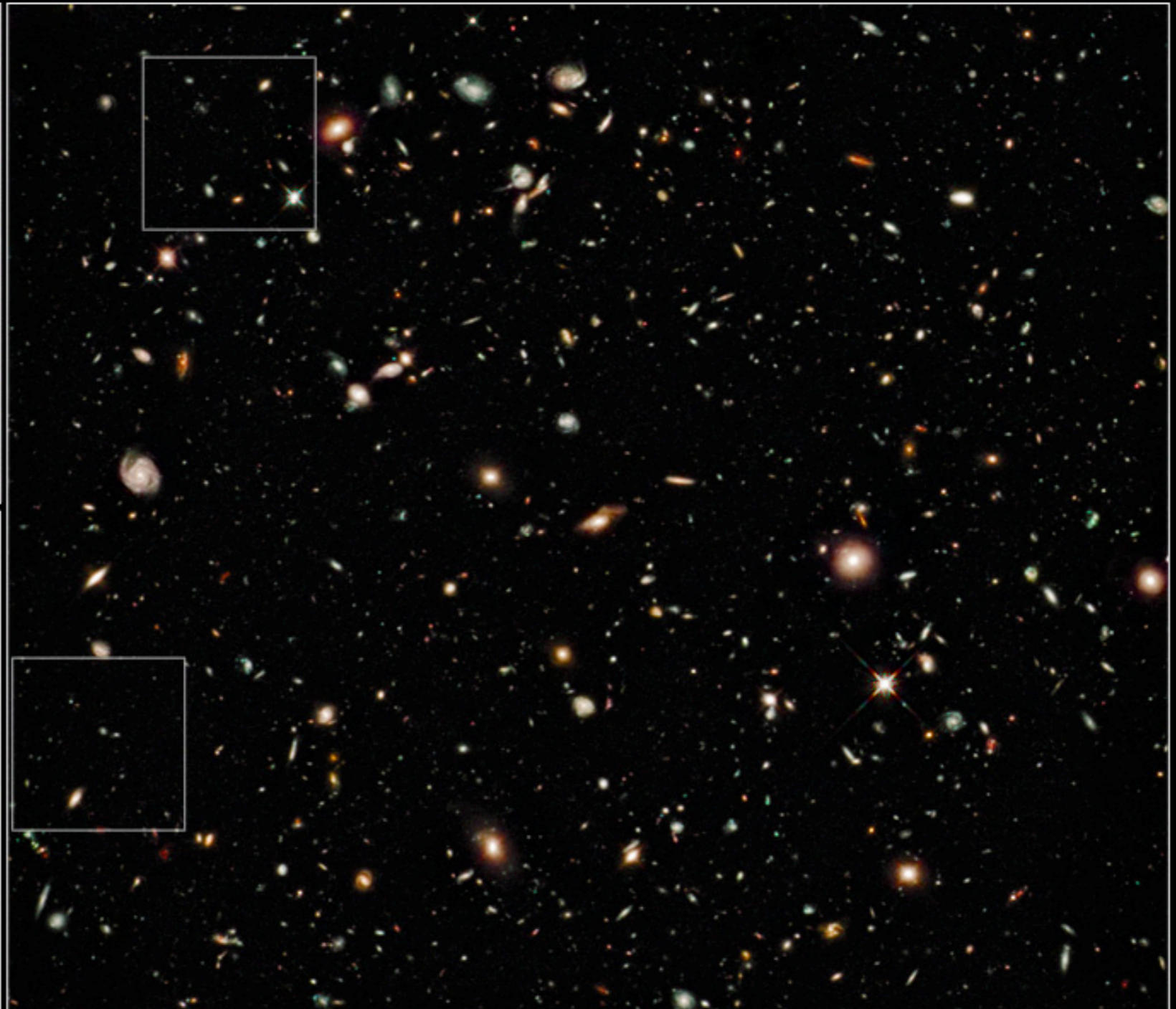
For many astronomers, this means “deep fields” to study galaxy light at high redshift, and to examine their luminosity, mass, star formation history, and other properties of the population.

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

Why Pursue the Fossil Record?

Hubble Ultra Deep Field • Infrared

Hubble Space Telescope • WFC3/IR



NASA, ESA, G. Illingworth (UCO/Lick Observatory and University of California, Santa Cruz), and the HUDF09 Team

STScI-PRC10-02

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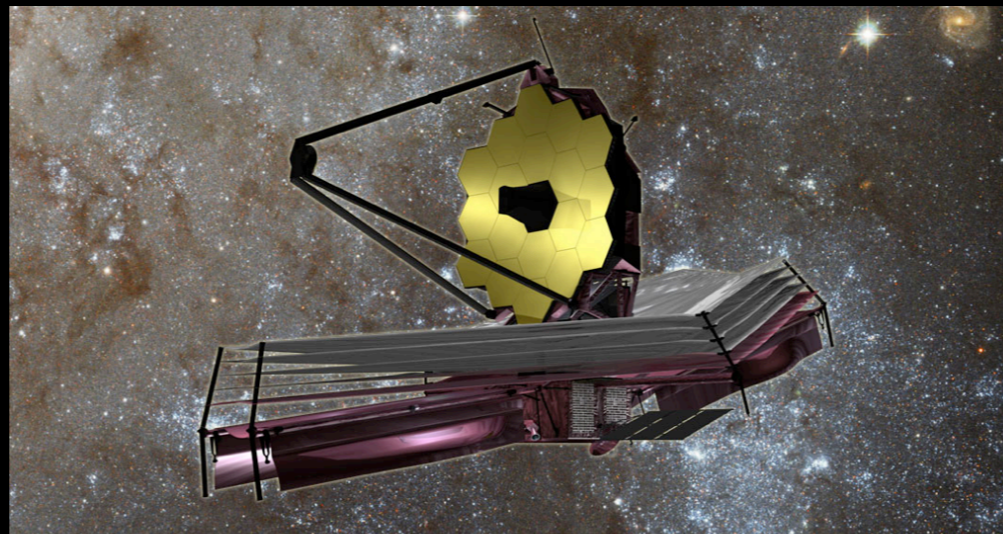
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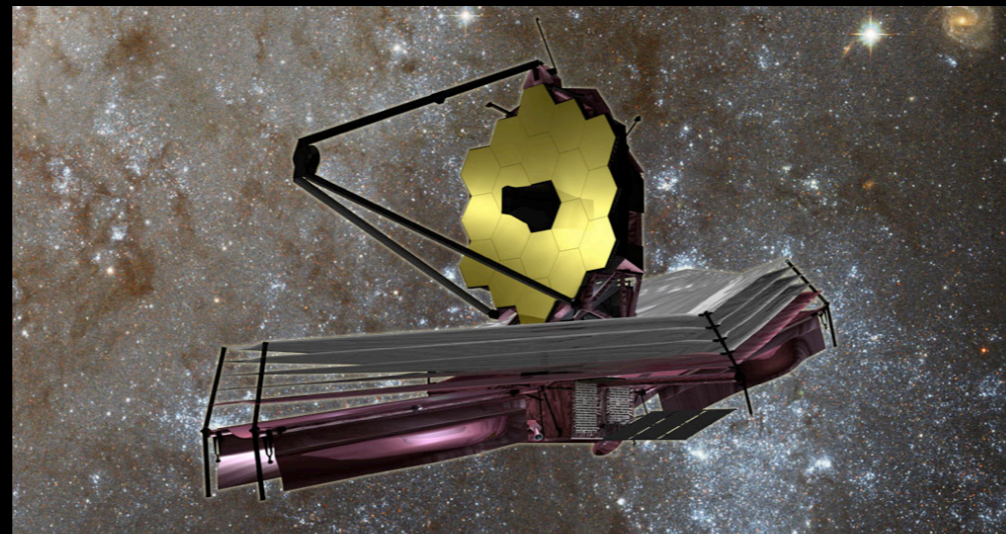


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But . . .

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)

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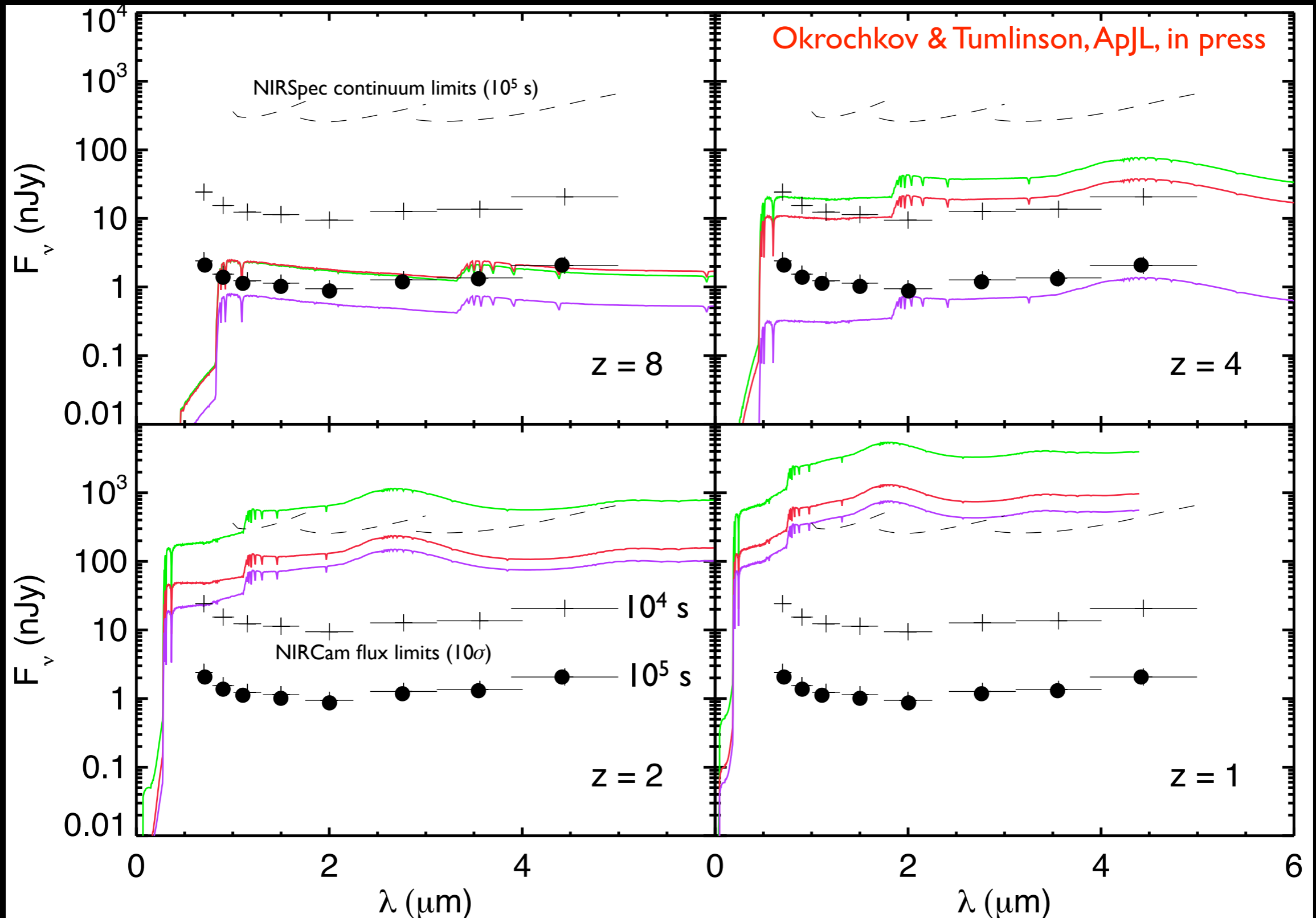
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It turns out that if our theory of the first stars is correct, it will be nearly impossible to detect them directly in the high-redshift Universe!

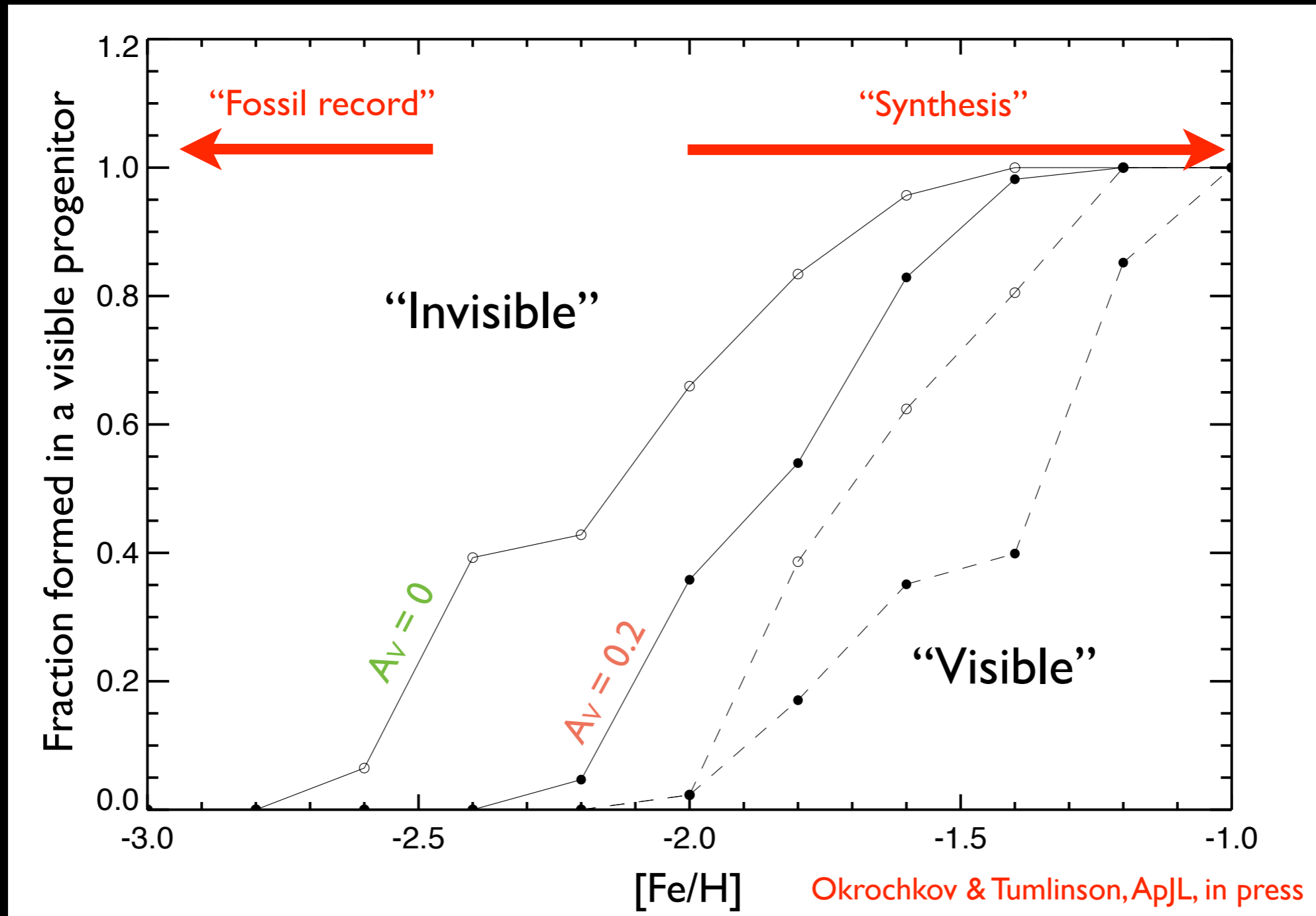
Now what?

High Redshift Visibility of Milky Way Progenitors



**MW progenitors visible to $z \sim 6 - 8$ in JWST deep fields (\sim 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



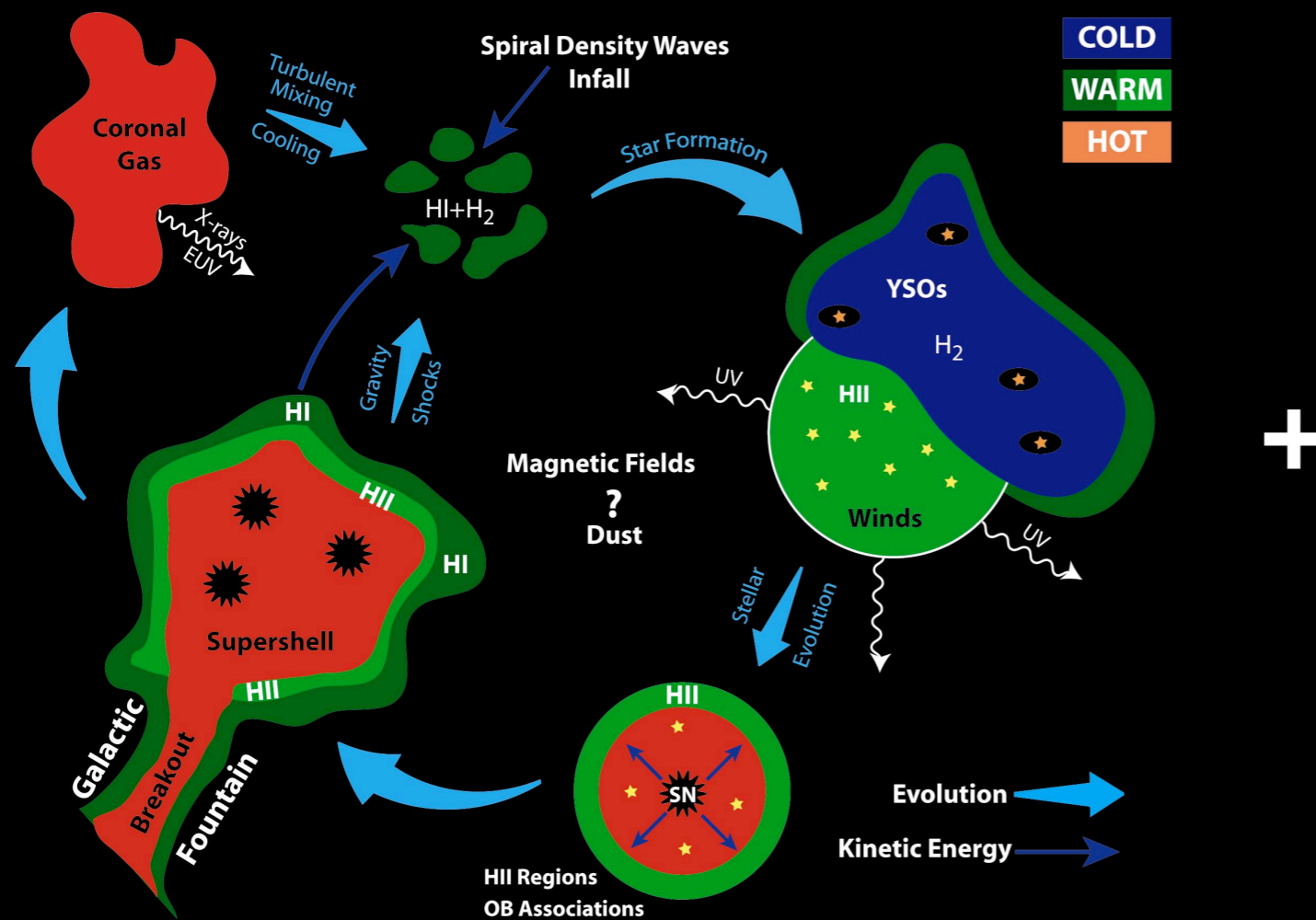
Now: there are two kinds of stars that survive in the MW halo.

- 1) Those that formed in progenitors NIRCam **can** see: $[\text{Fe}/\text{H}] \approx -2$
- 2) Those that formed in progenitors NIRCam **cannot** see: $[\text{Fe}/\text{H}] \approx -2$

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

The Problem

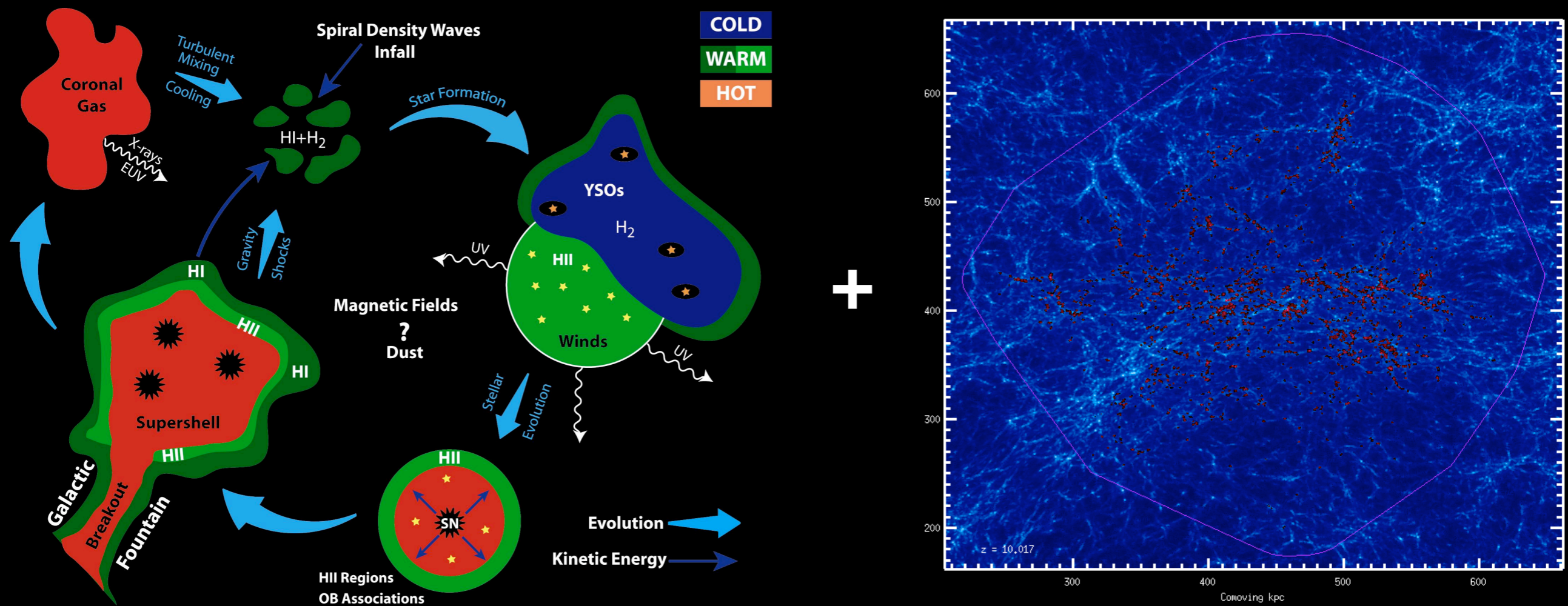
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Cons	<ol style="list-style-type: none"> 1. Poor “spatial resolution” 2. Not easy to make hierarchical 3. Not really stochastic either. 		

Analytic Models for Galactic Disks

Chemical evolution models for spiral disks: the Milky Way, M31 and M33 [arXiv:1004.4139](https://arxiv.org/abs/1004.4139)

M. M. Marcon-Uchida^{1,2} *, F. Matteucci^{1,3}, and R. D. D. Costa²

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

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.

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

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

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 responsible for the uncertainties 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 $1Gyr^{-1}$ 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

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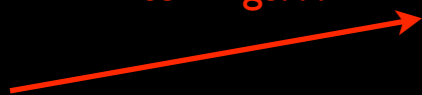
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Galactic disk divided into rings...



Analytic Models for Galactic Disks

Chemical evolution models for spiral disks: the Milky Way, M31 and M33 [arXiv:1004.4139](https://arxiv.org/abs/1004.4139)

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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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Infall tracked into each ring

Star formation rate tracked in each ring

Model yields put in

Analytic Models for Galactic Disks

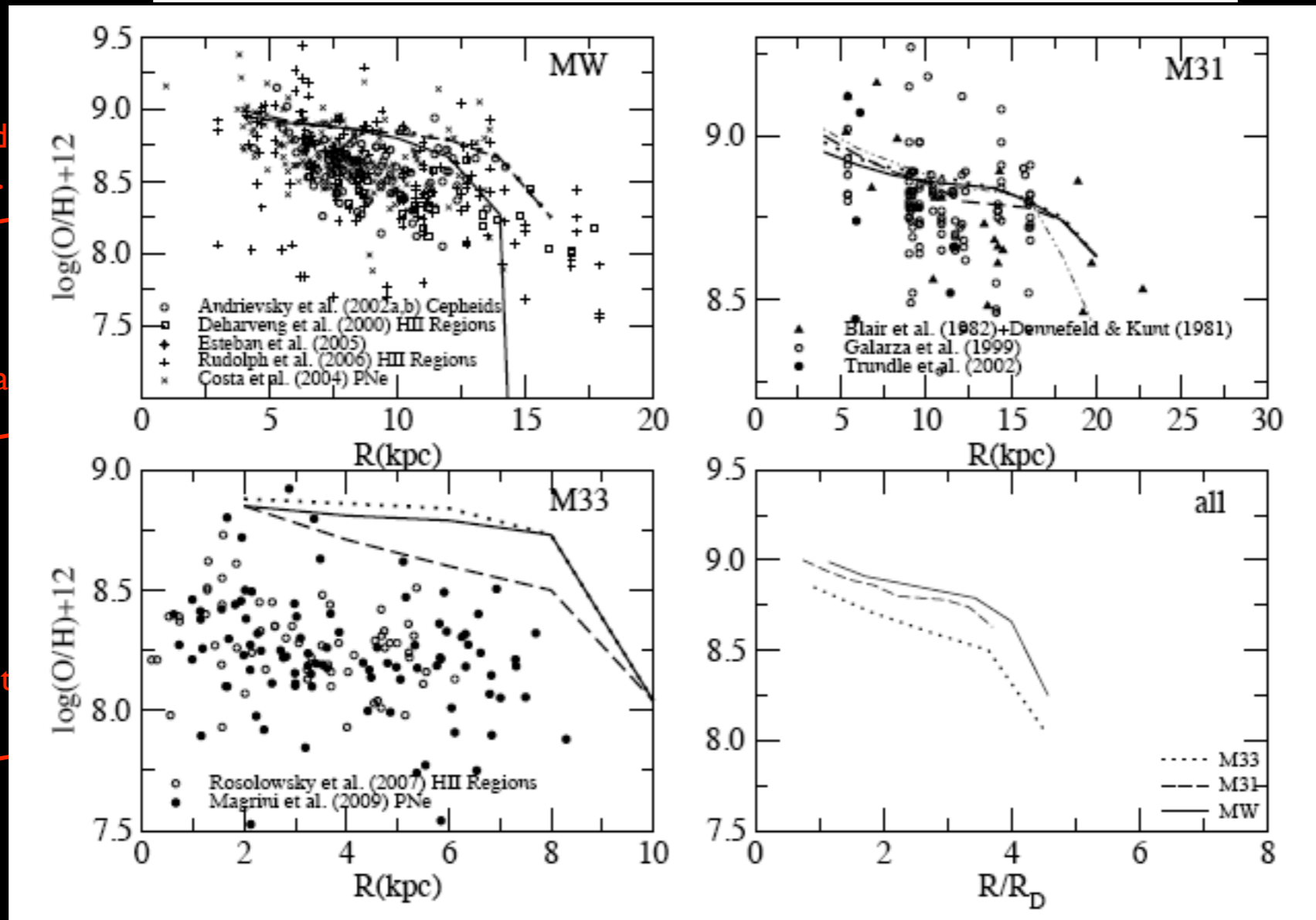
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Galactic disk divided into rings.

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Star formation rate tracked in each ring.

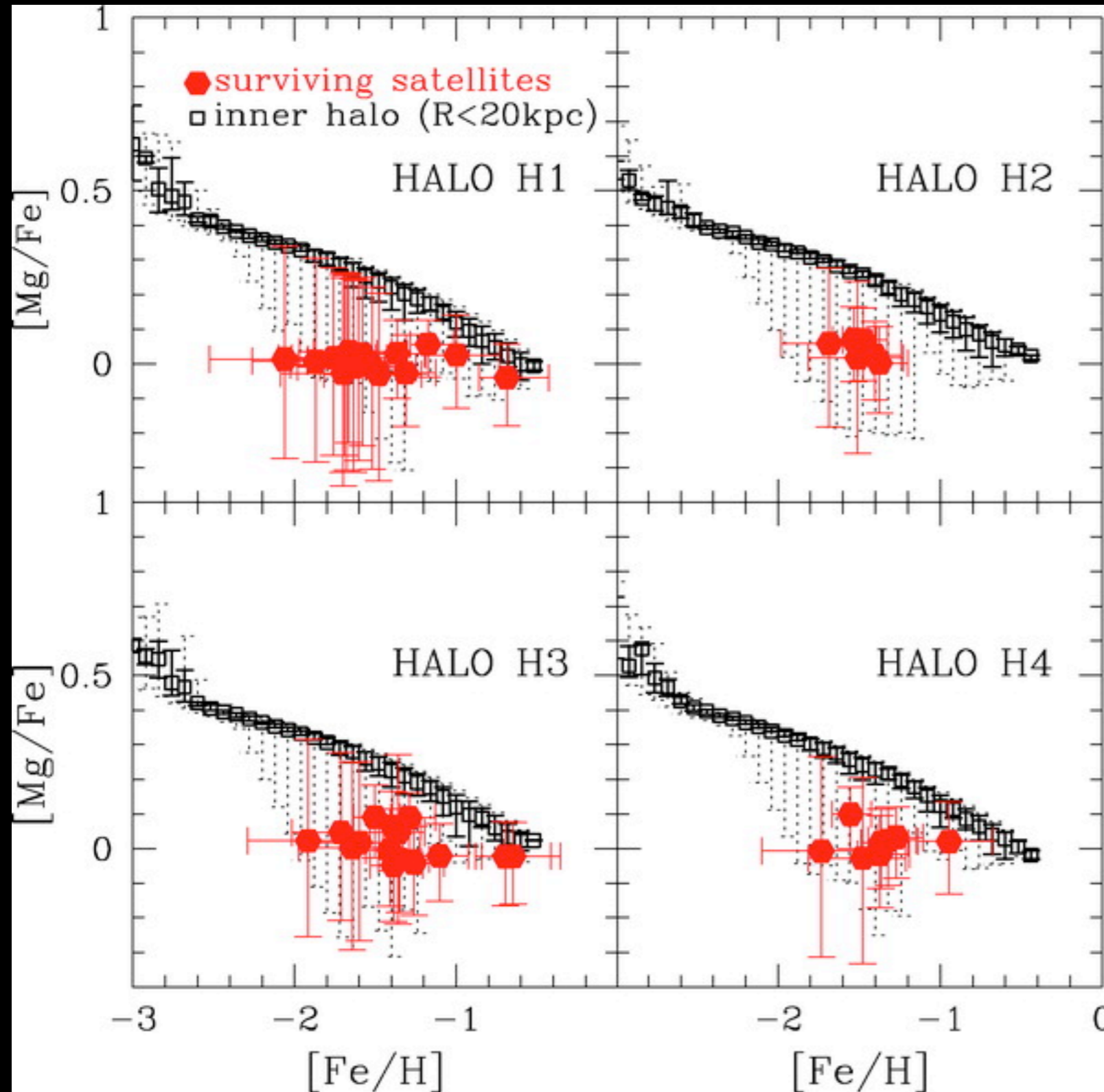
Model yields put in.

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

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.	
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Pros	<ol style="list-style-type: none"> 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. 	<ol style="list-style-type: none"> 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	<ol style="list-style-type: none"> 1. Poor “spatial resolution” 2. Not easy to make hierarchical 3. Not really stochastic either. 	<ol style="list-style-type: none"> 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)

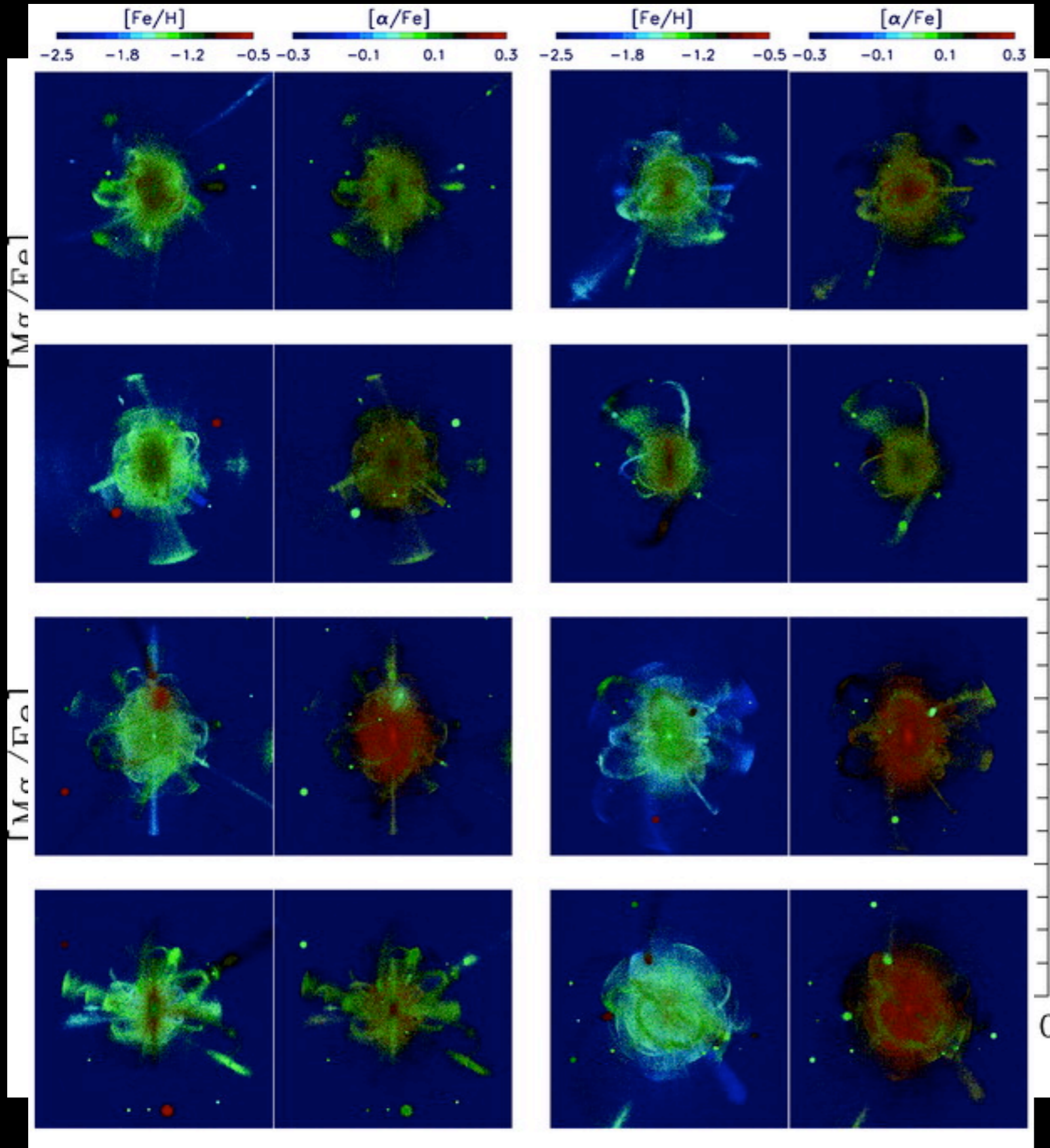
Synthetic stellar halos built on top of N-body simulations of an isolated halo.

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

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

Education

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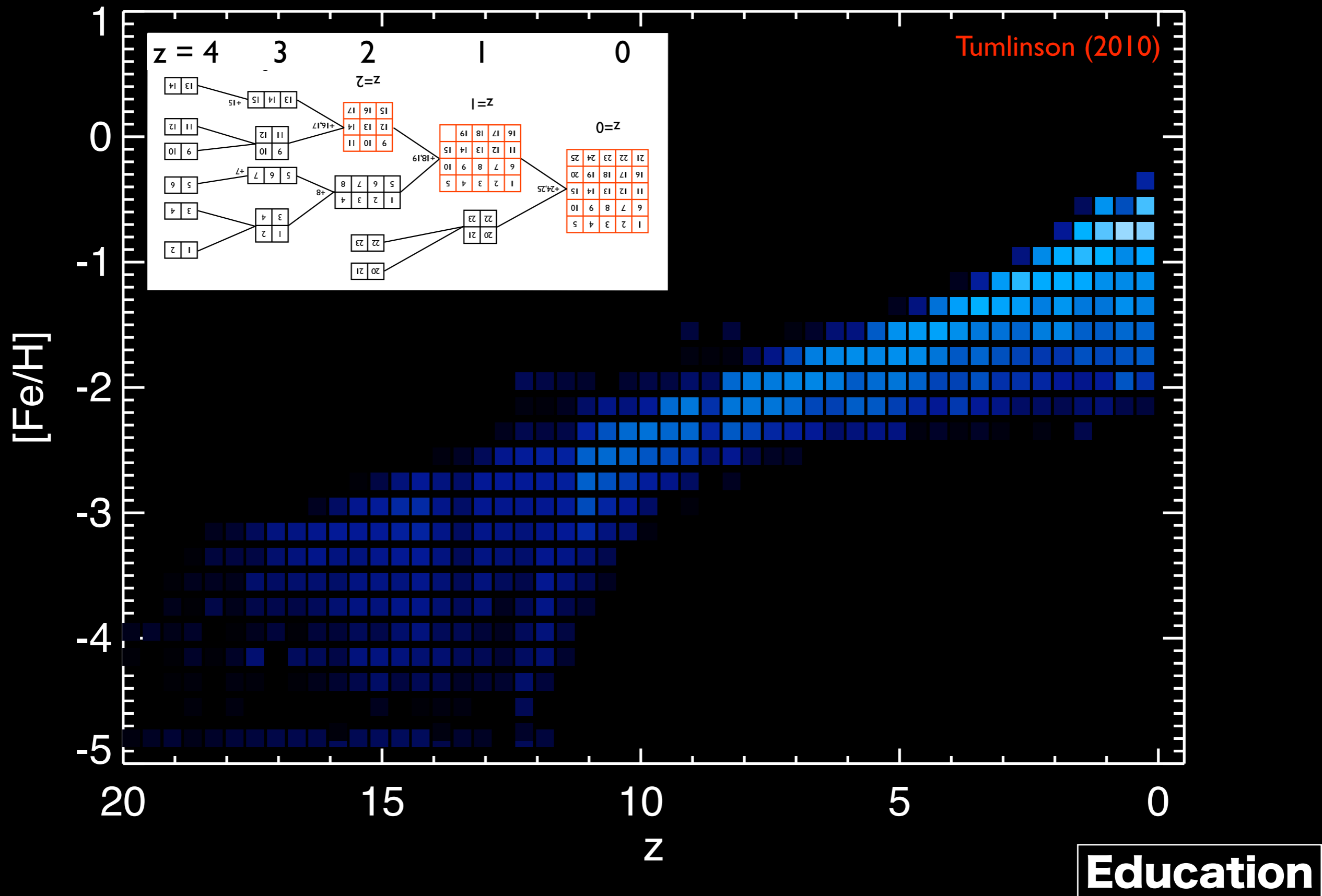
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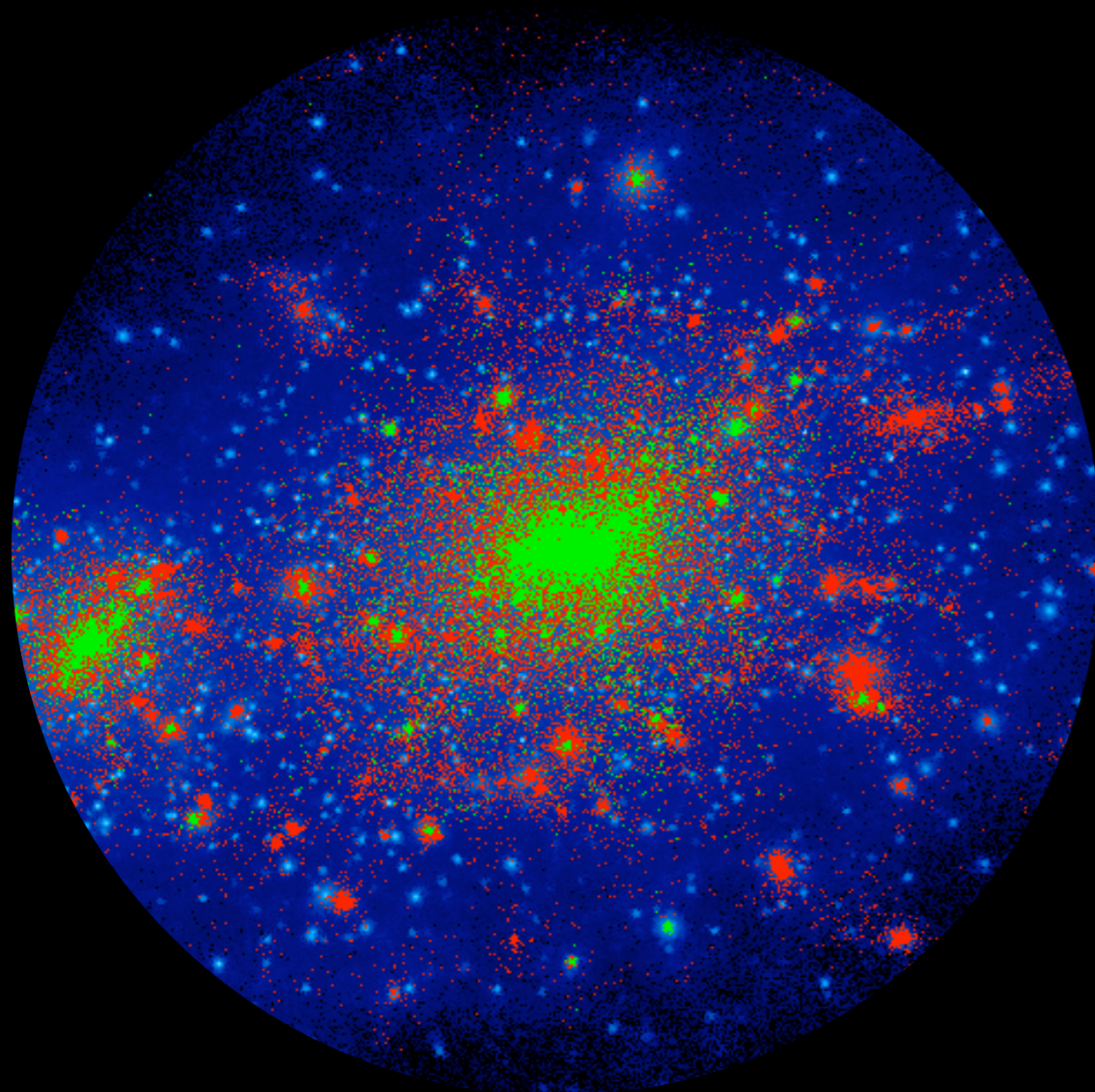
Hierarchical, Stochastic Models and the MW



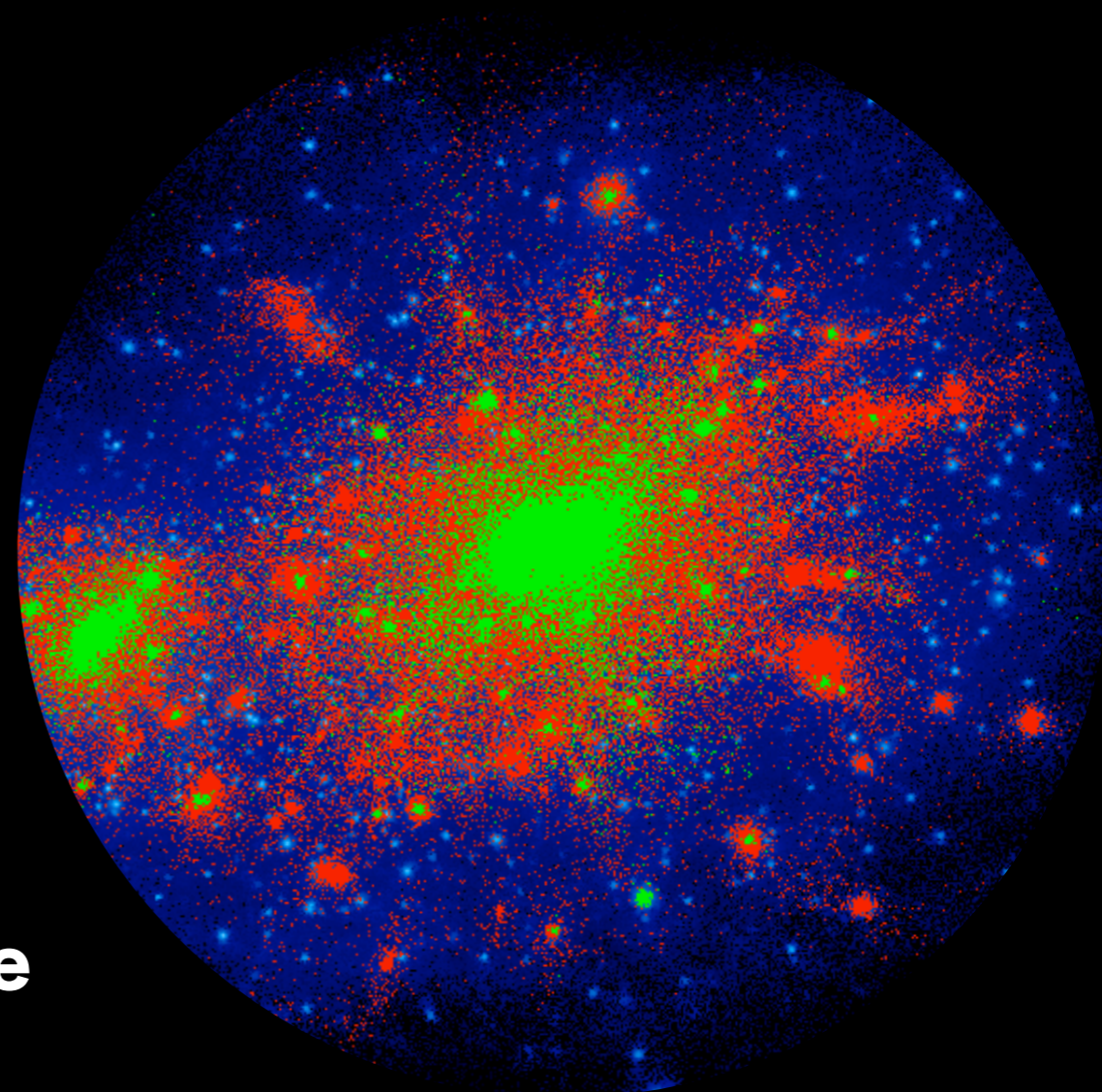
Semi-Analytics and the First Galaxies

stars formed $z > 10$
stars formed at all z

$[\text{Fe}/\text{H}] < -2.0$



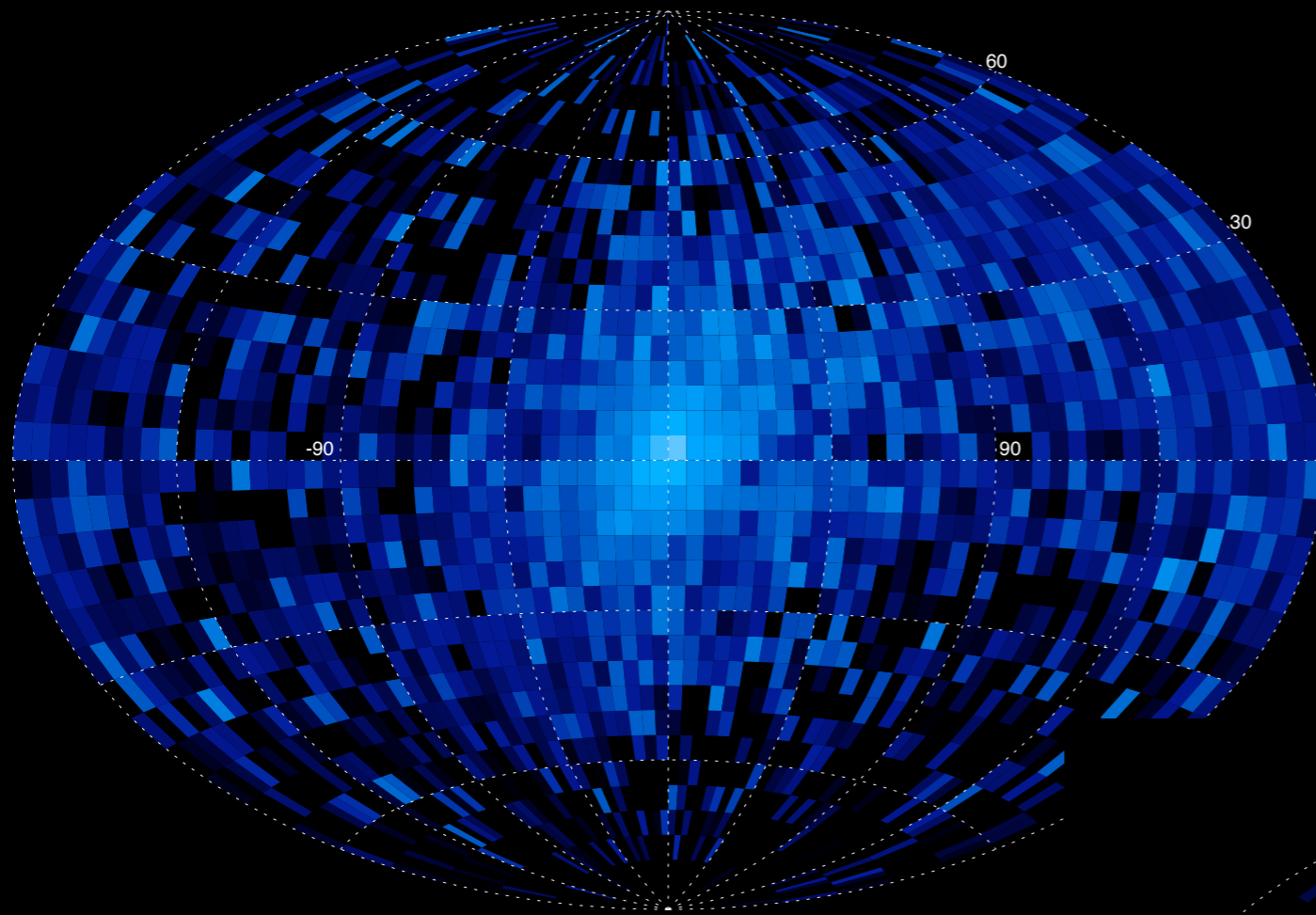
$[\text{Fe}/\text{H}] < -3.5$



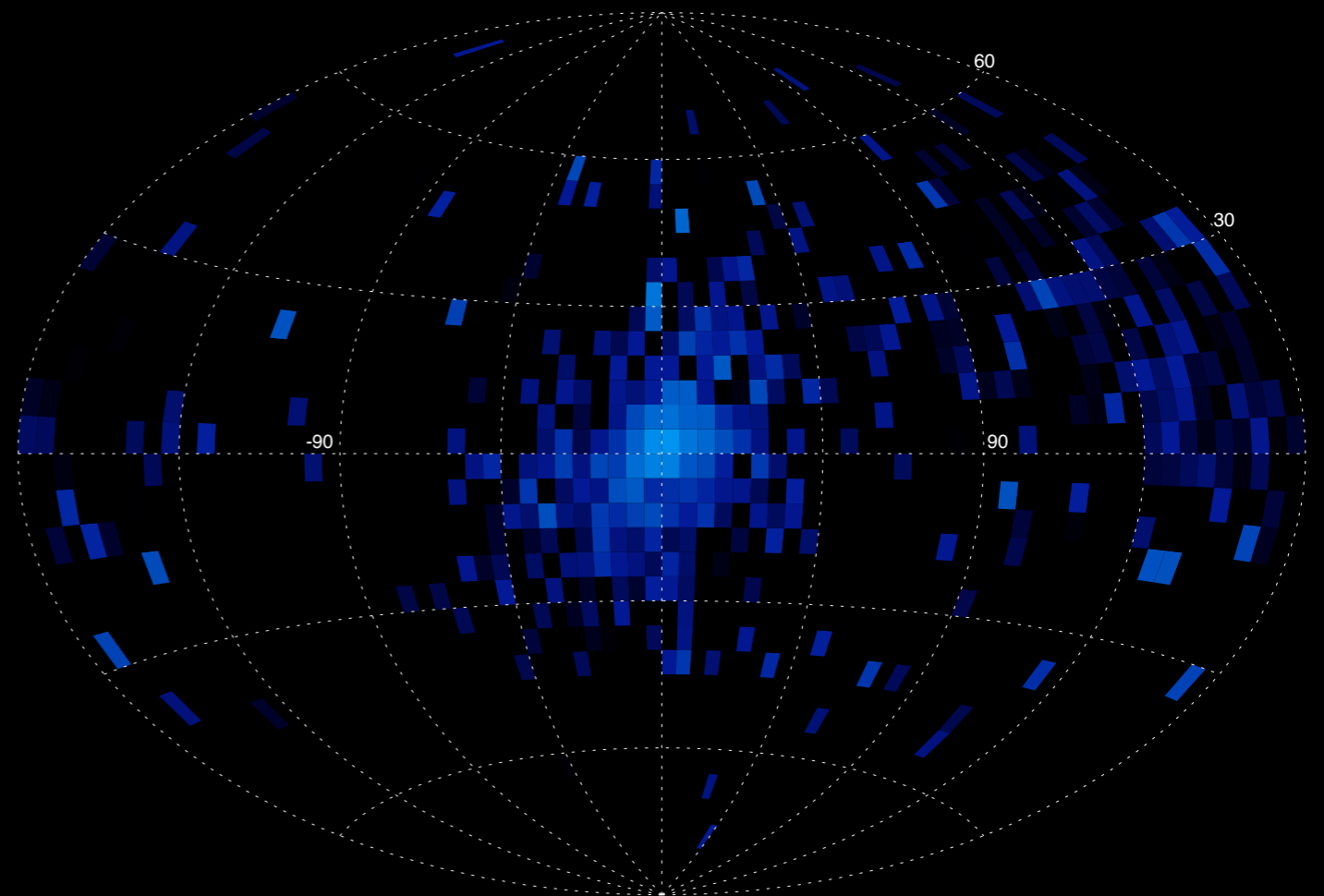
Chronologically older stars are more centrally concentrated.

Education

All Stars with $[Fe/H] < -3$



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



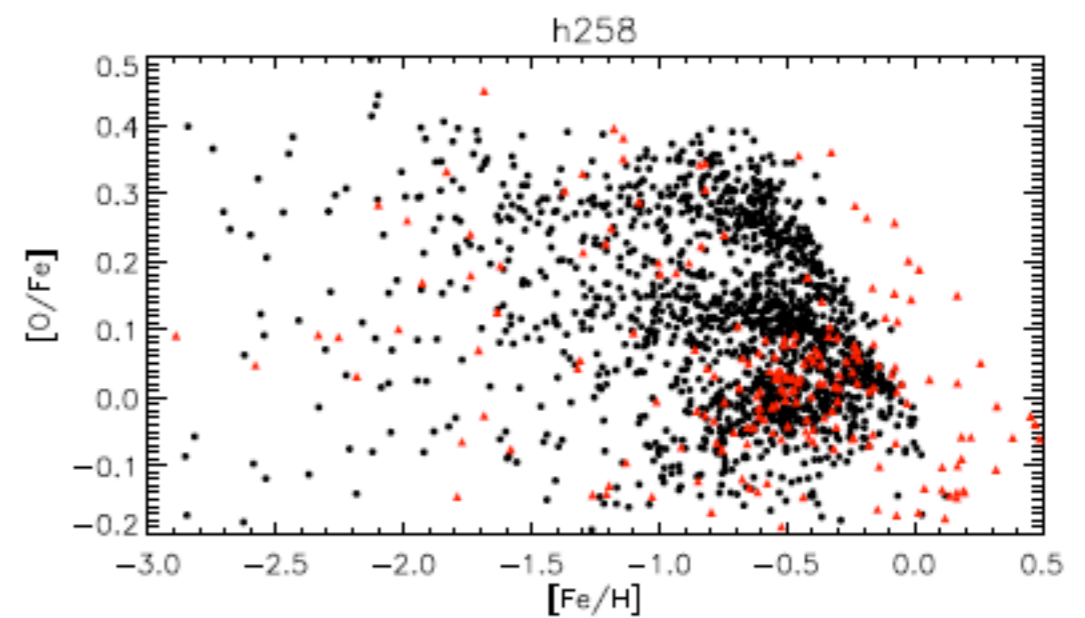
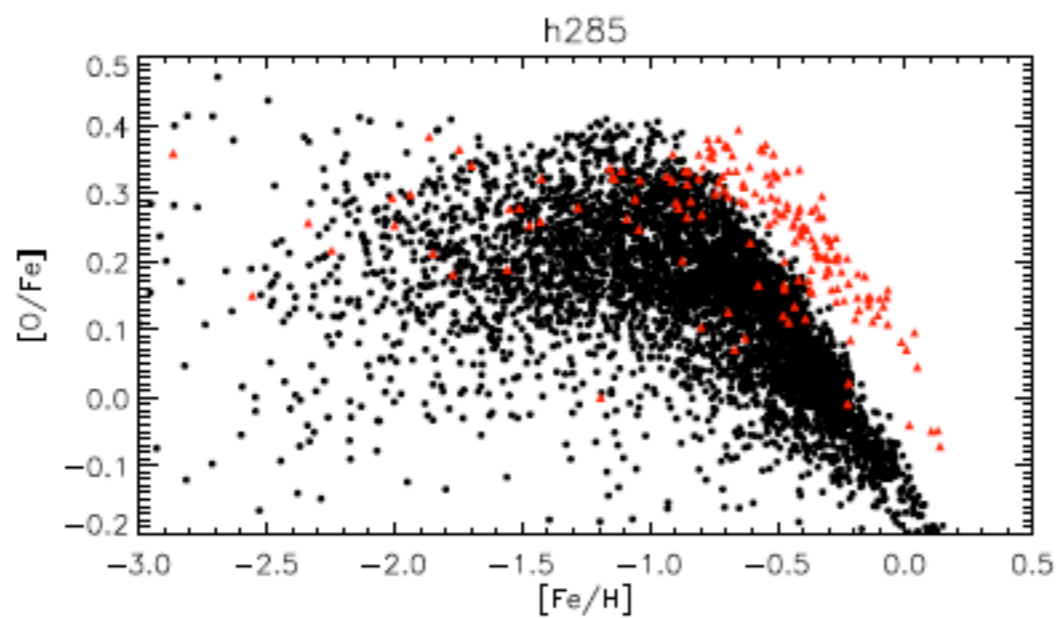
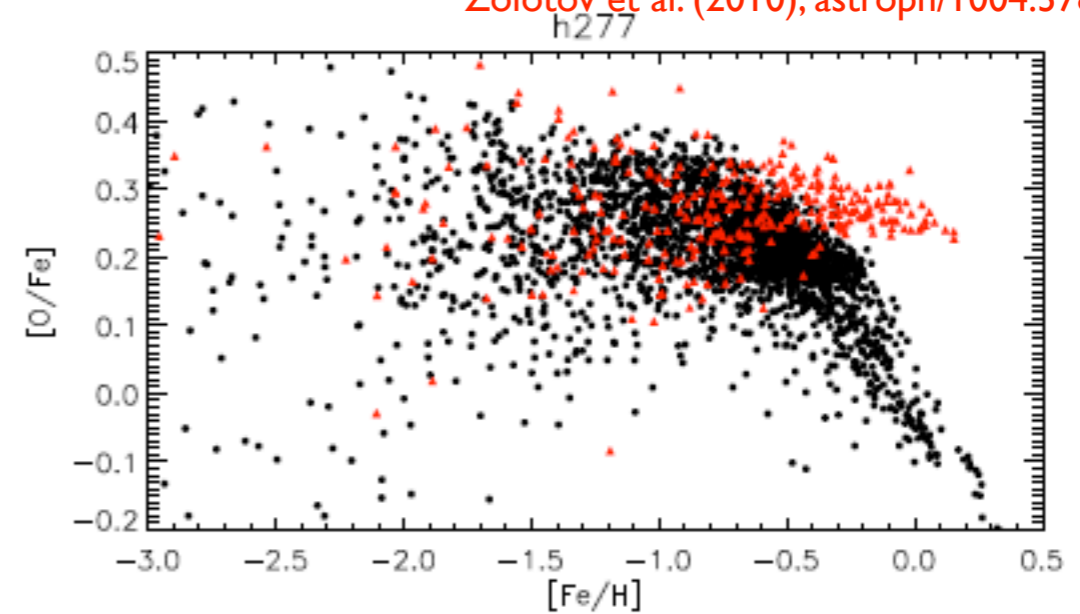
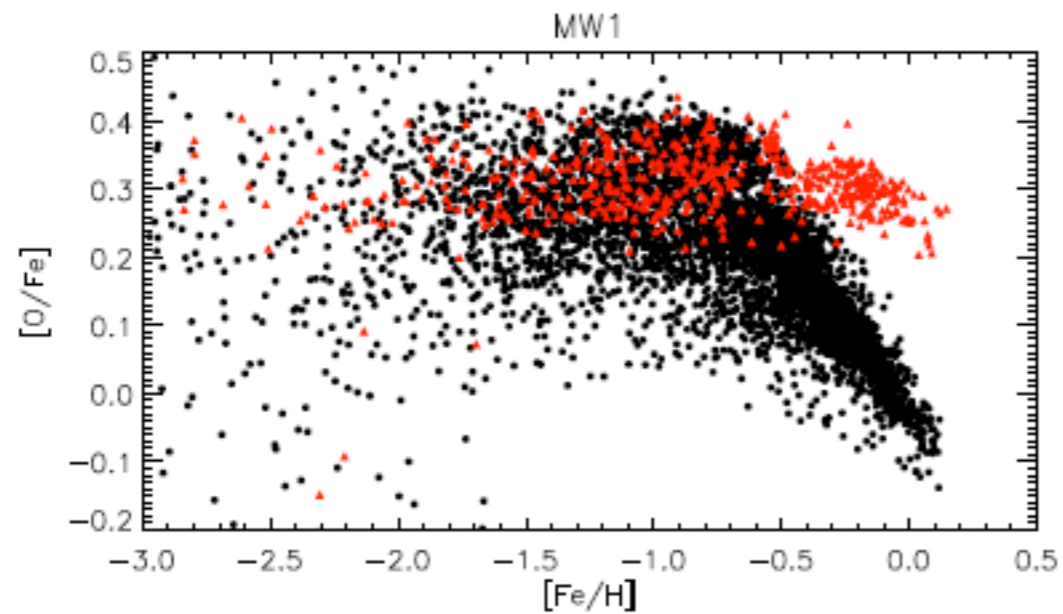
The most ancient stars are
“in the bulge” but not “of
the bulge”.

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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 Λ CDM. Tag stellar populations back to particles in the N-body simulation.	Track passively advected chemical tracer fields for each interesting element. Explicit inclusion of mass and energy return in stellar winds and supernovae. All within a cosmological box.
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A Late-Breaking Example from GASOLINE

Zolotov et al. (2010), astro-ph/1004.3789



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

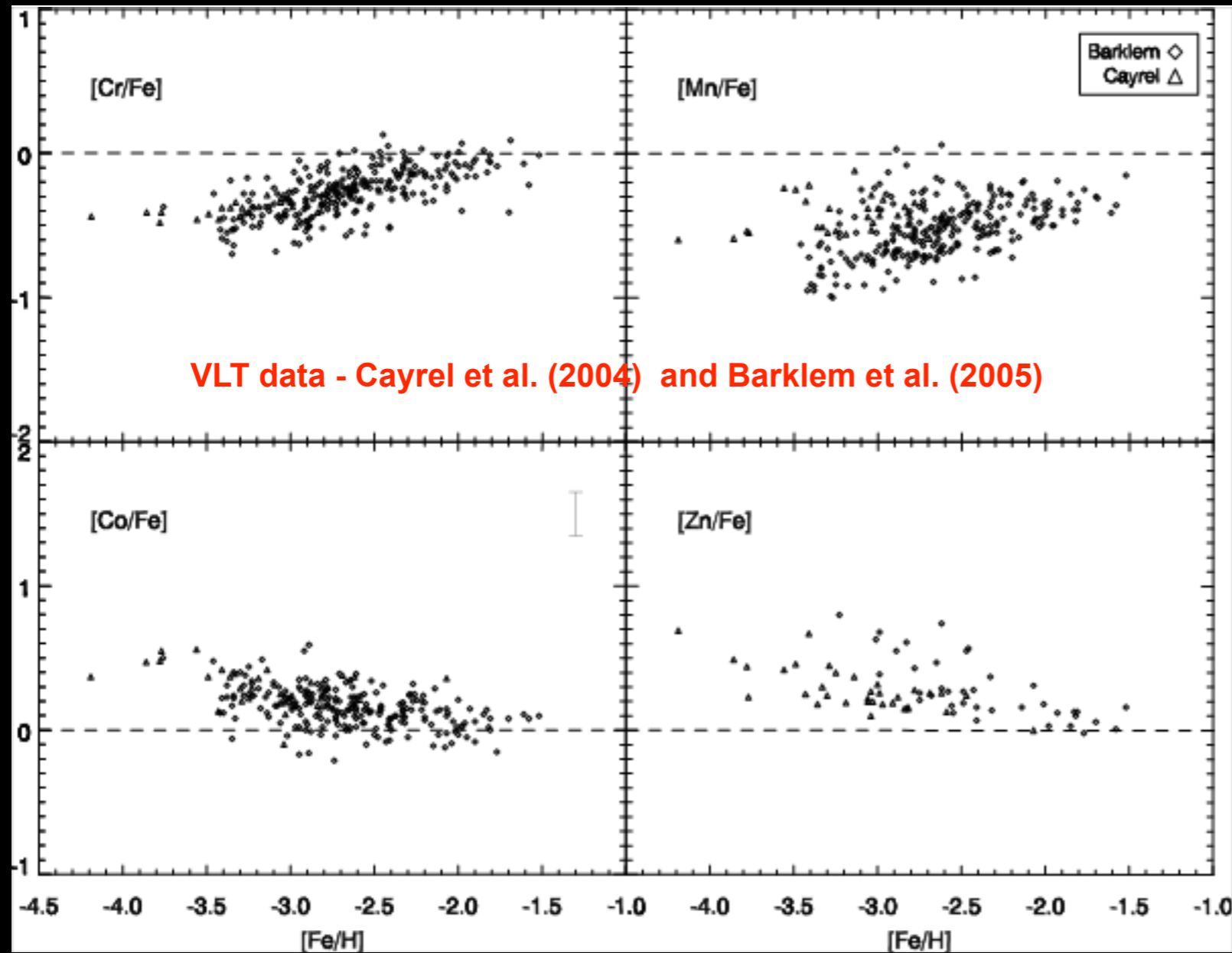
**What have we already
done to extract info
from the fossil record,
and what are its
limitations?**



Progress

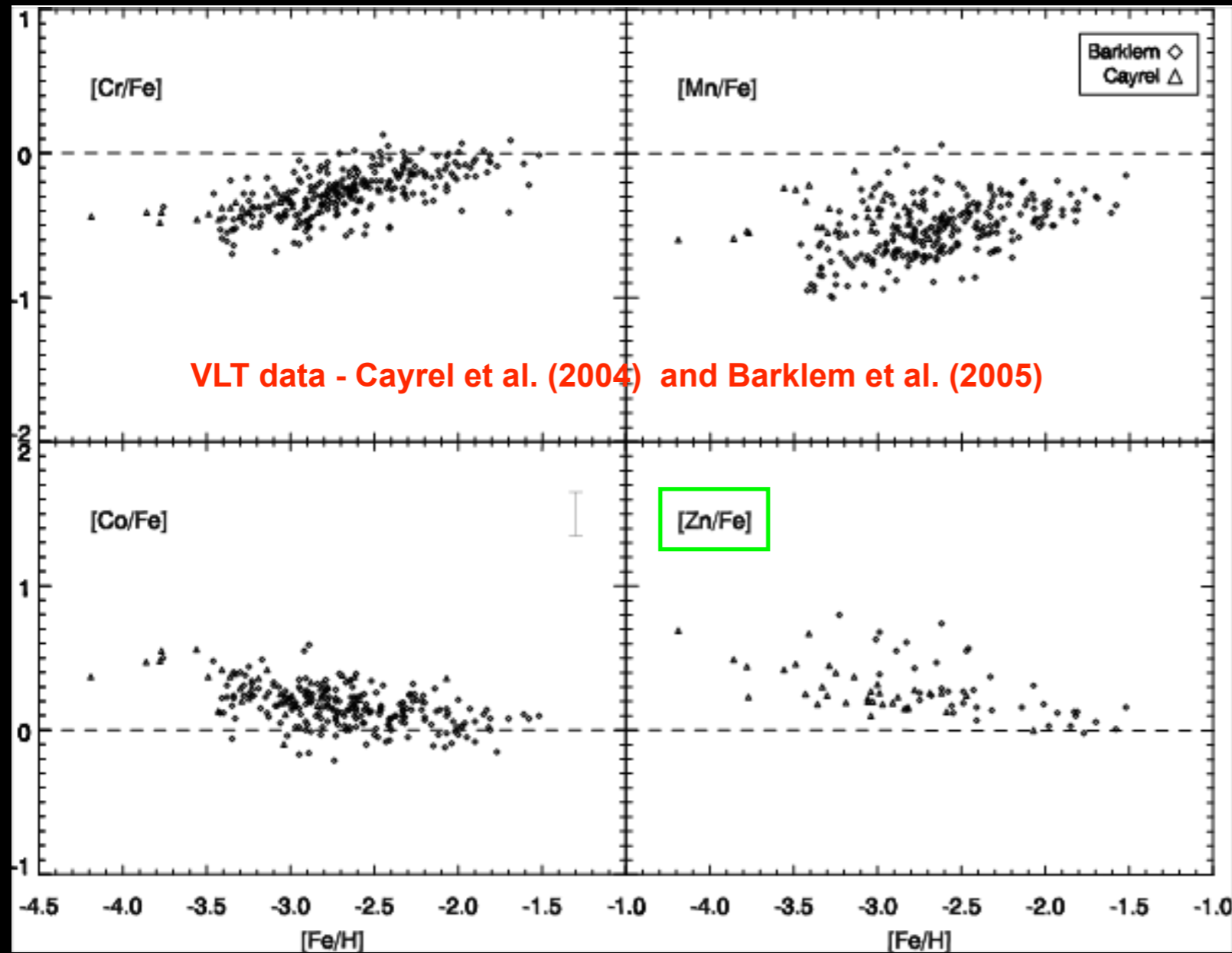
Ignorance

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



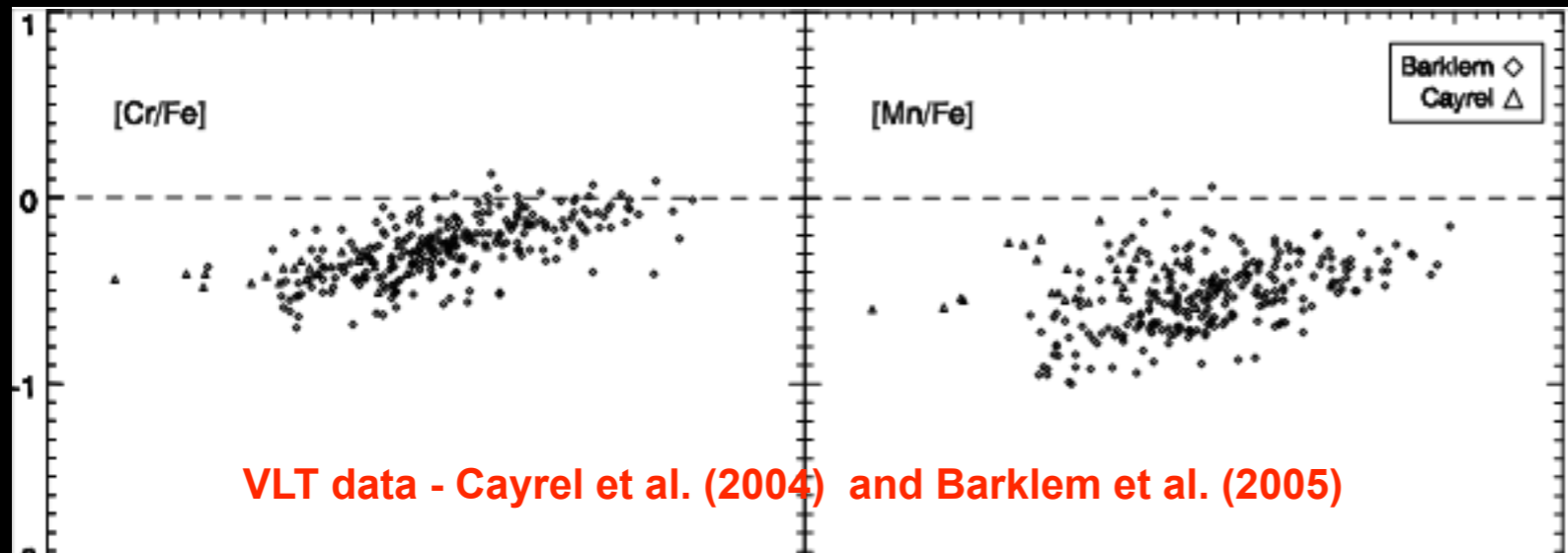
Illustration

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

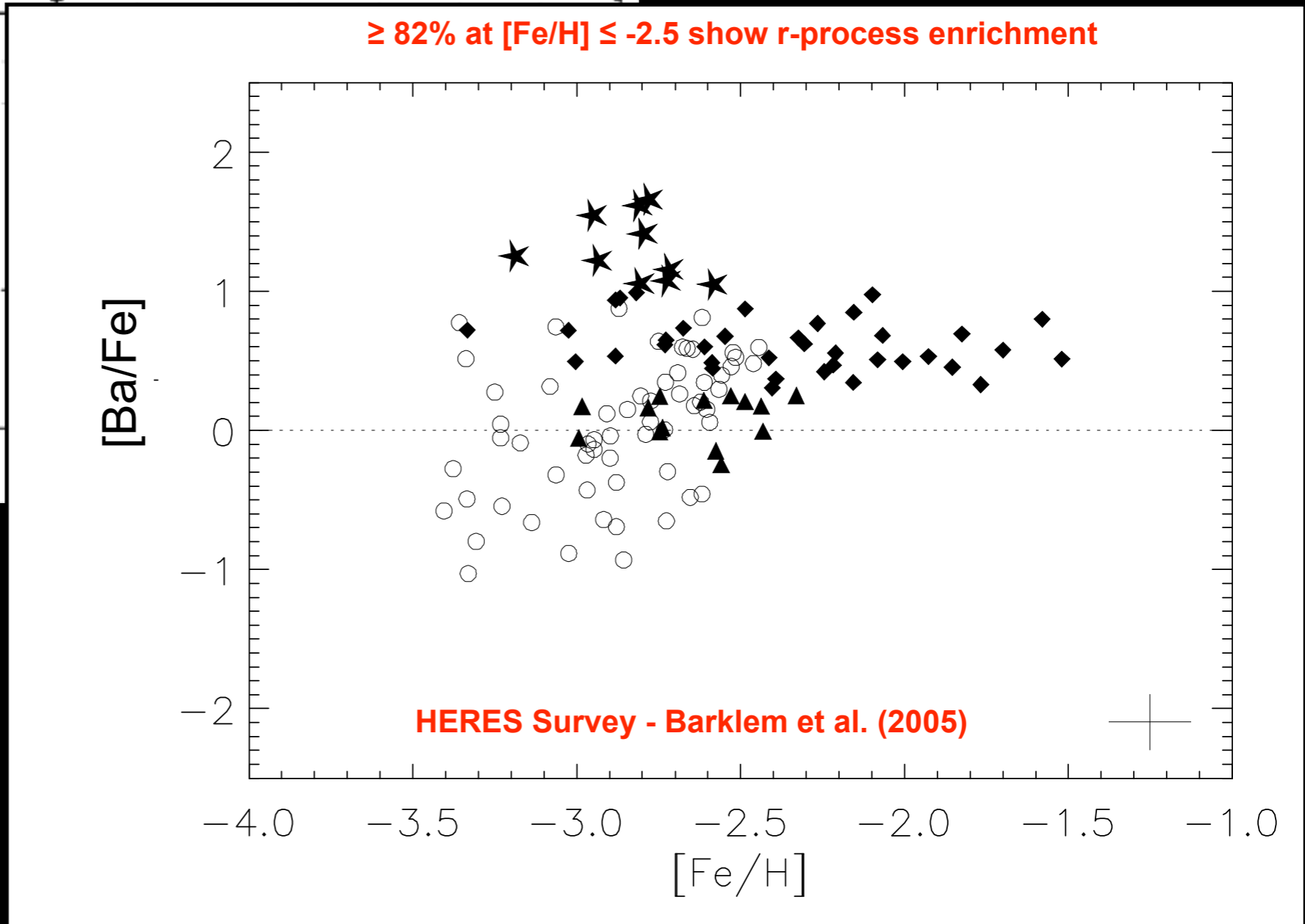
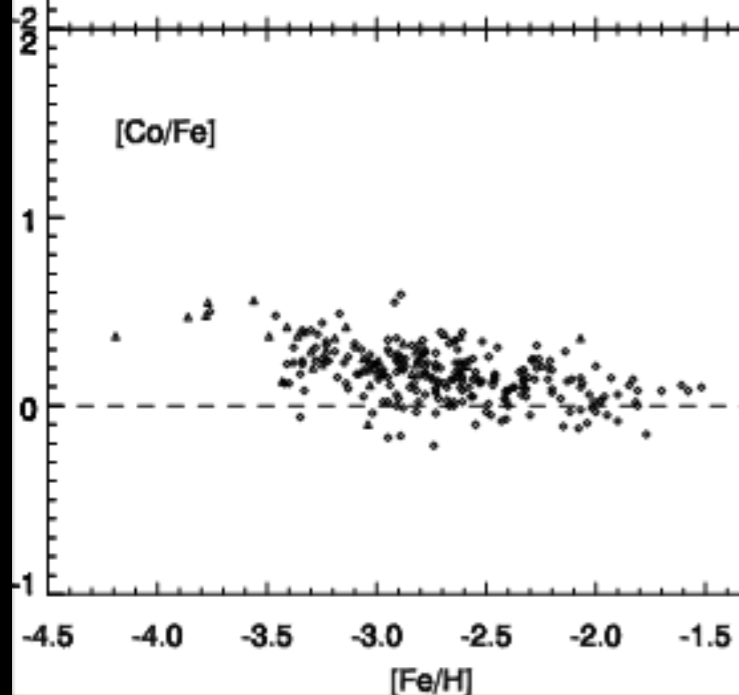


Illustration

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VLT data - Cayrel et al. (2004) and Barklem et al. (2005)

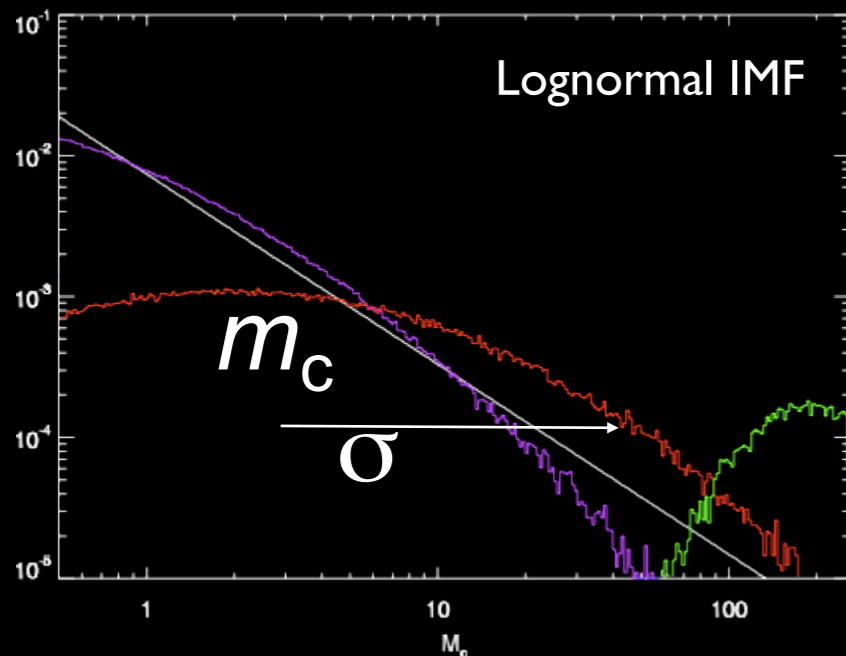
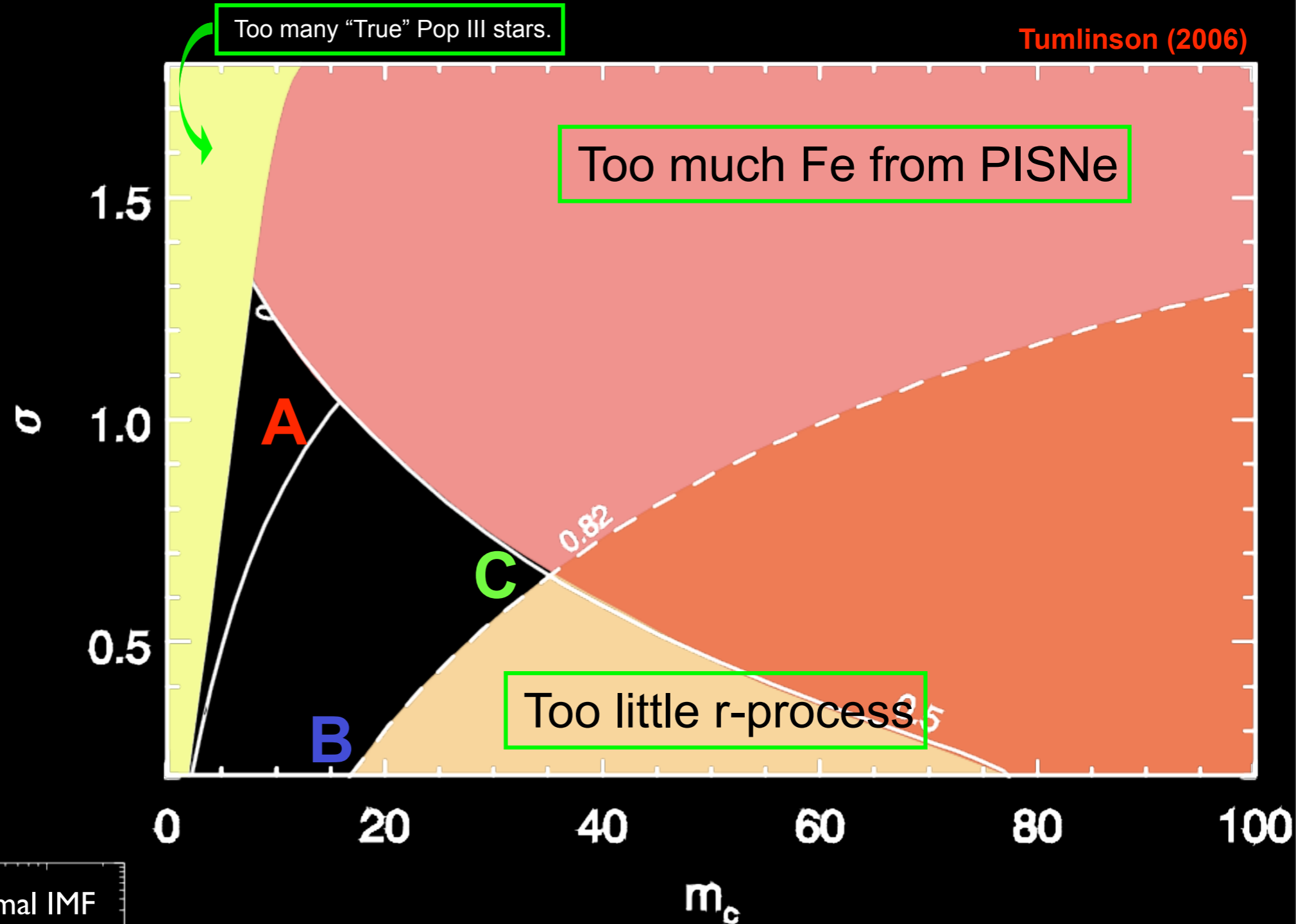


HERES Survey - Barklem et al. (2005)

Illustration

Illustration

Tumlinson (2006)

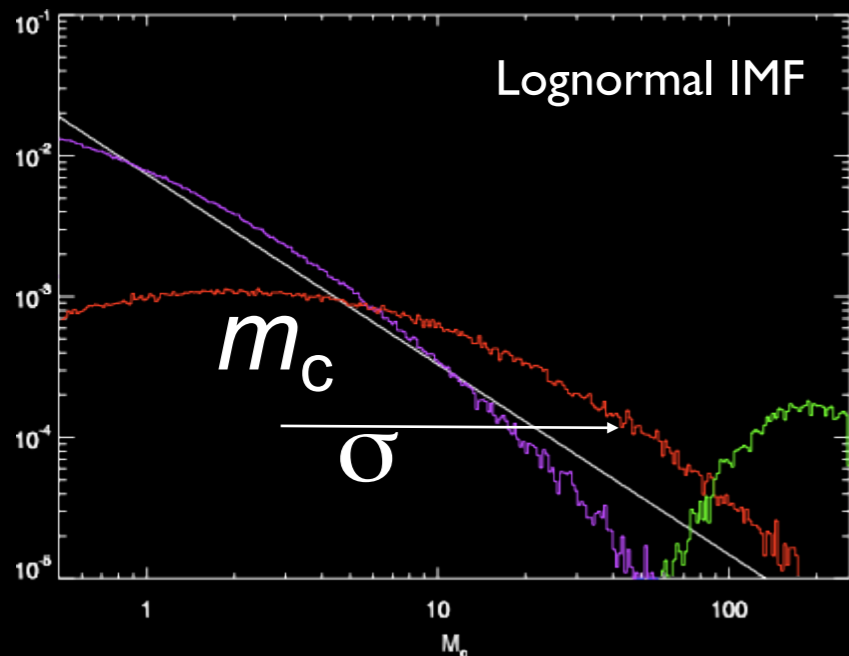
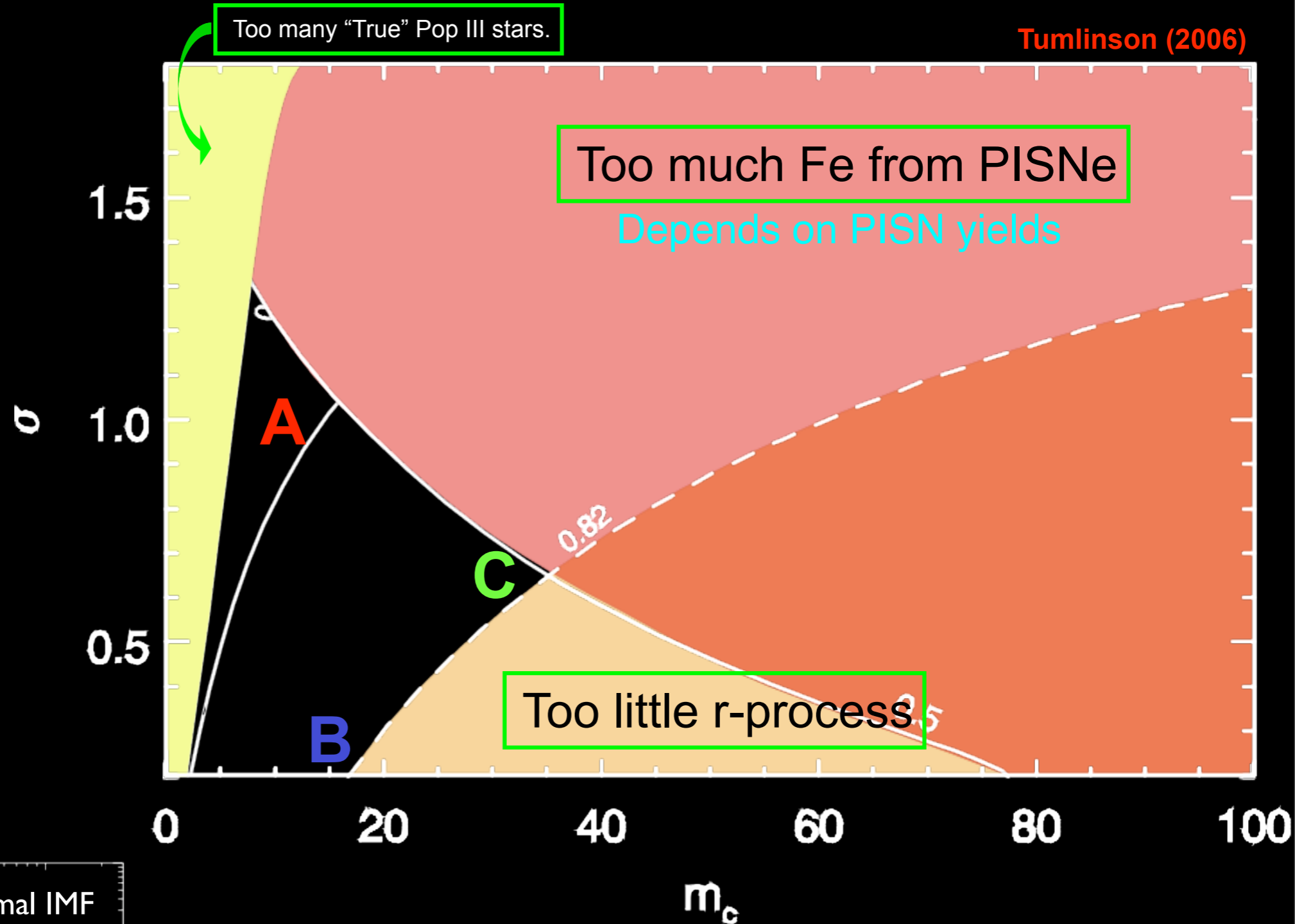


30% Progress: We have shown that these abundances do provide leverage in the interesting mass range.

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

Tumlinson (2006)

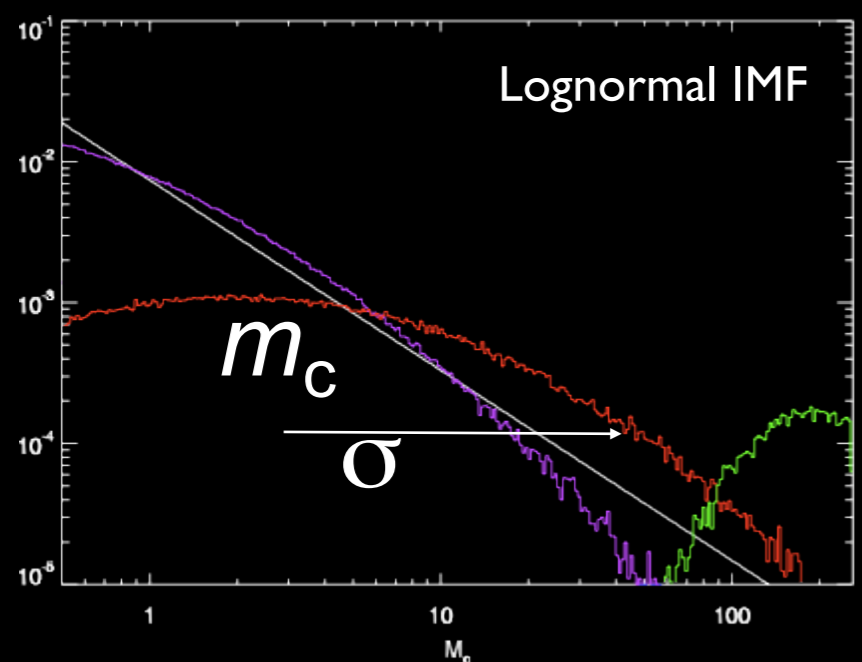
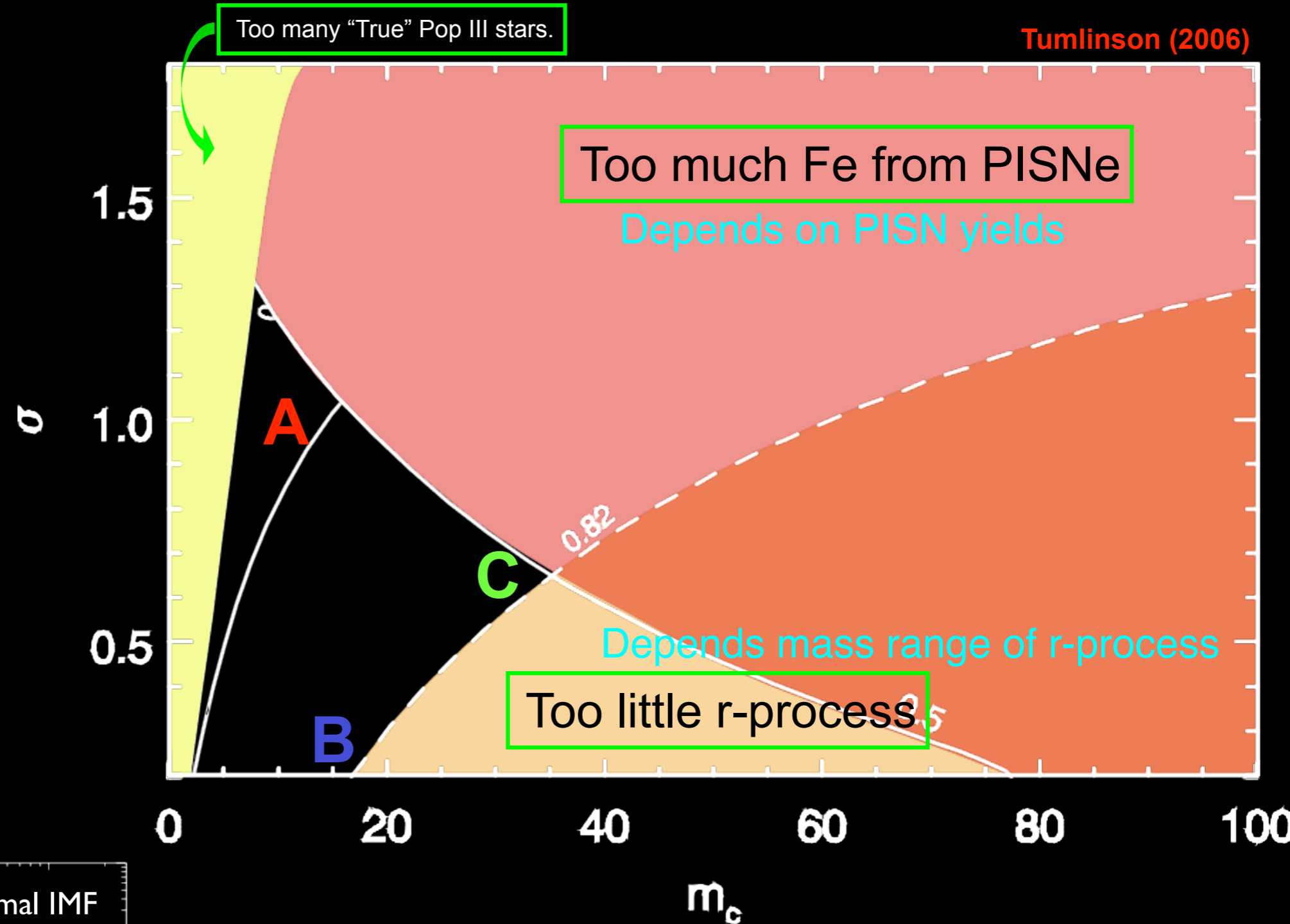


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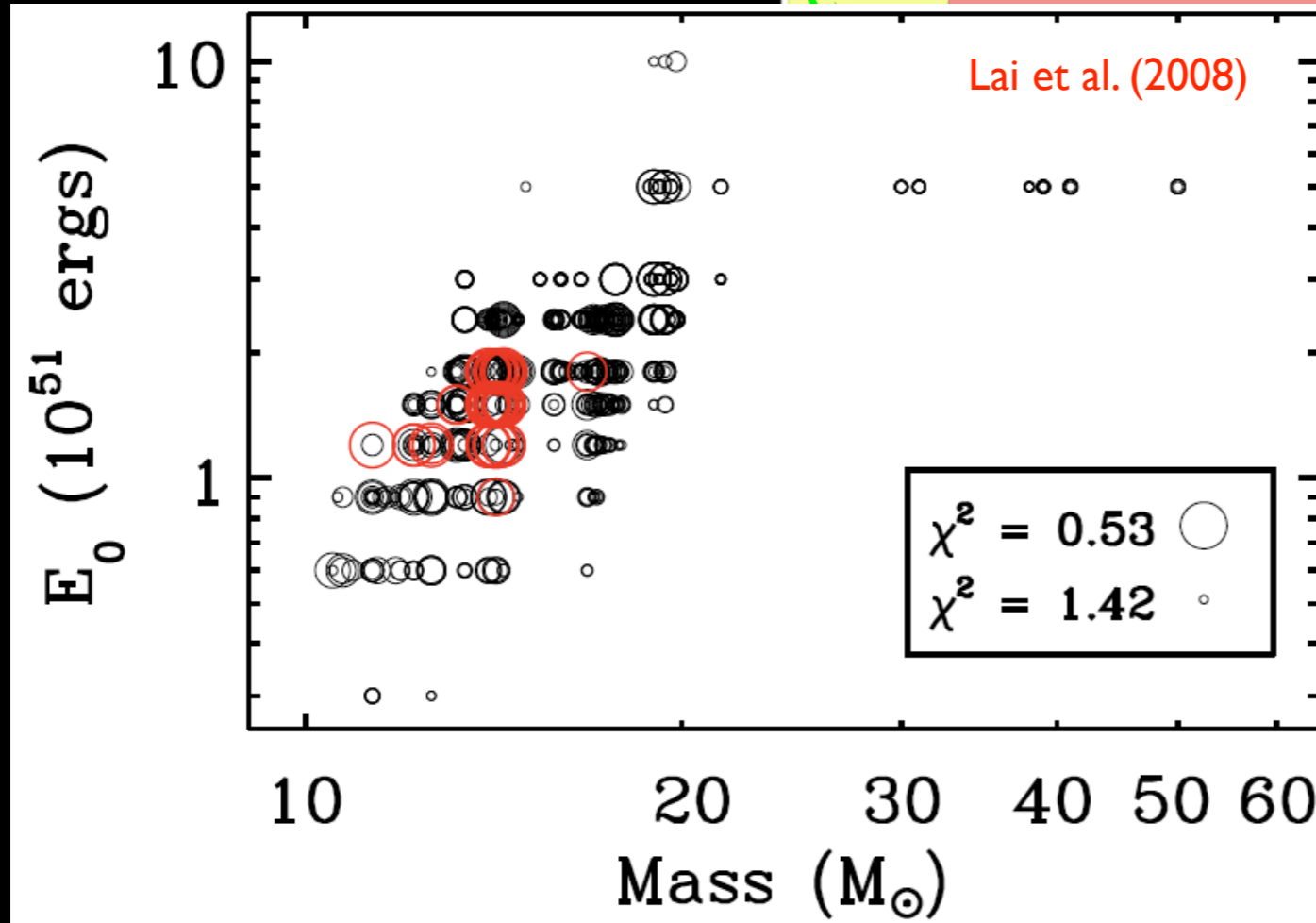
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Illustration

Too many "True" Pop III stars.

Tumlinson (2006)

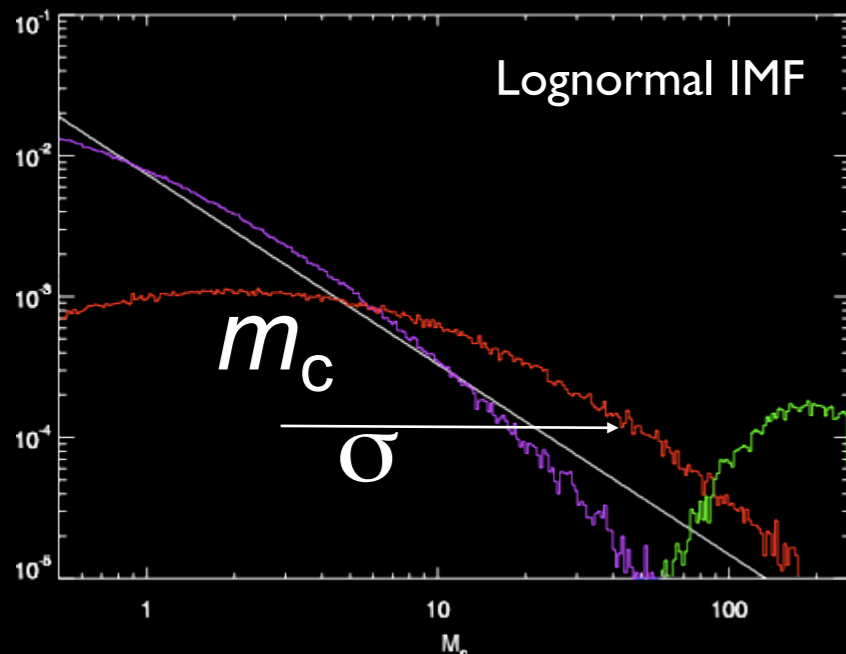
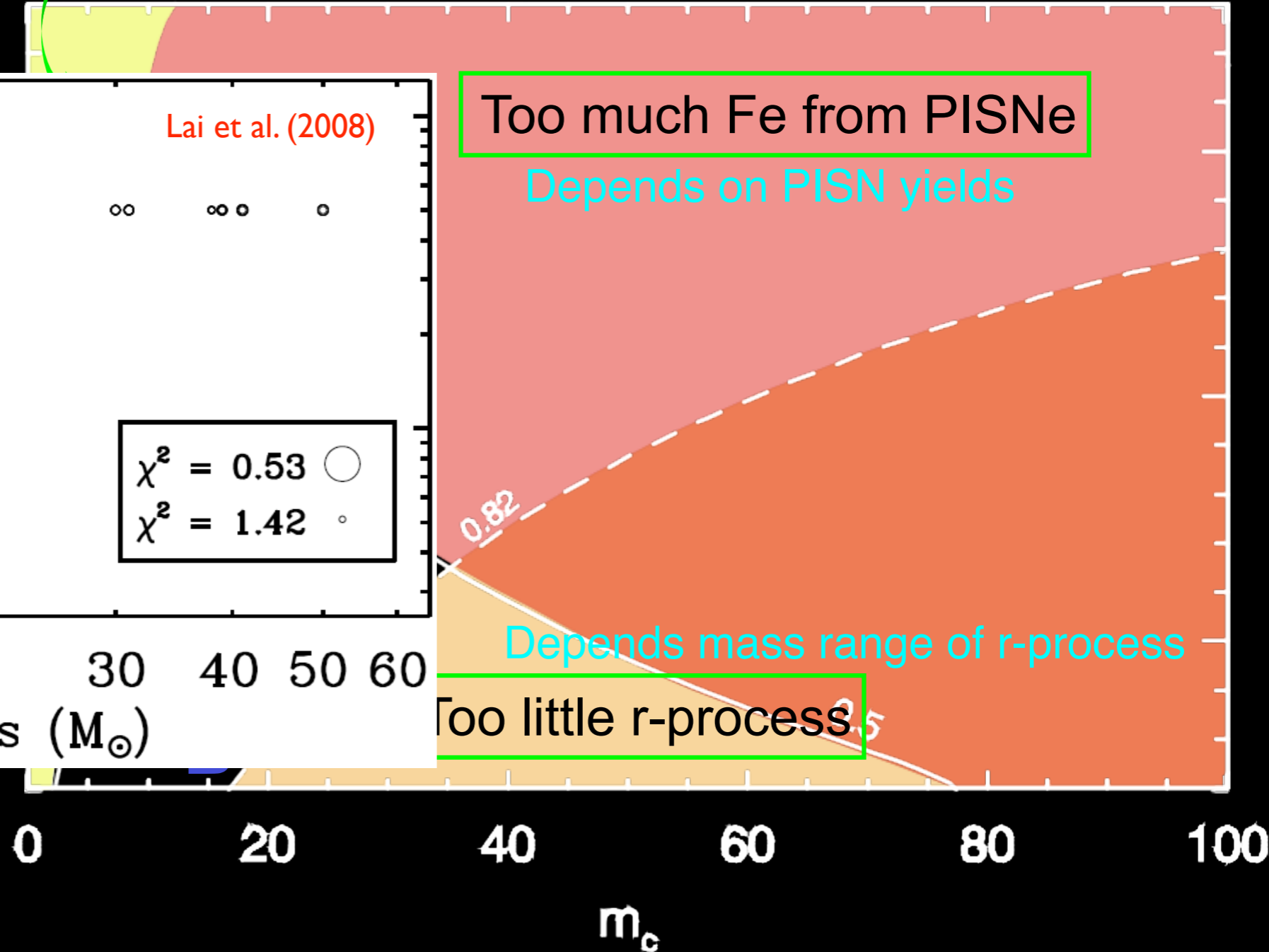


Too much Fe from PISNe

Depends on PISN yields

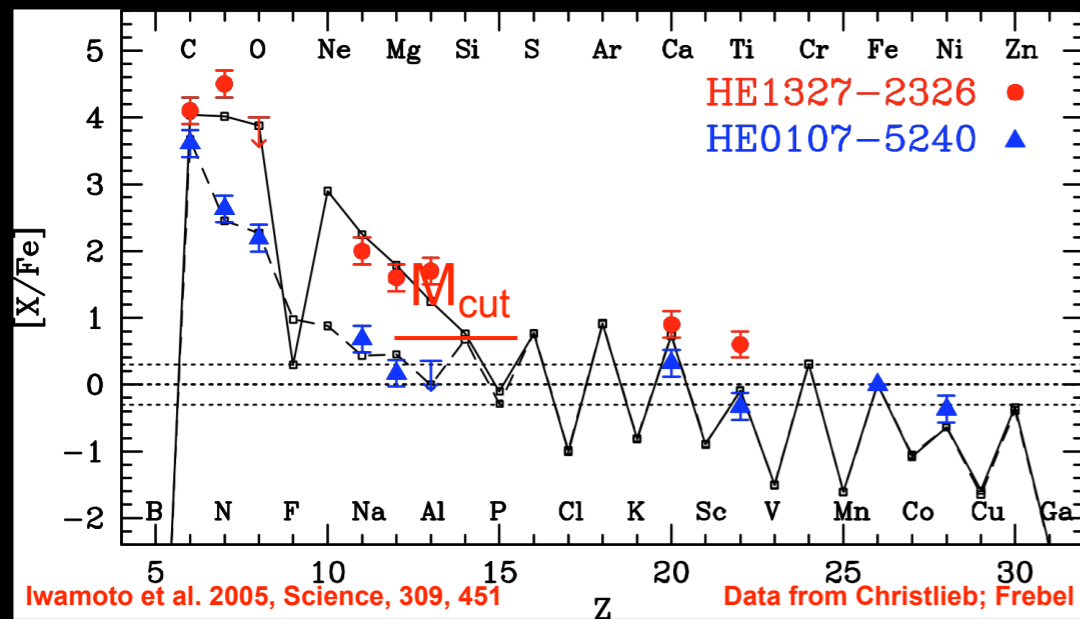
Depends mass range of r-process

Too little r-process

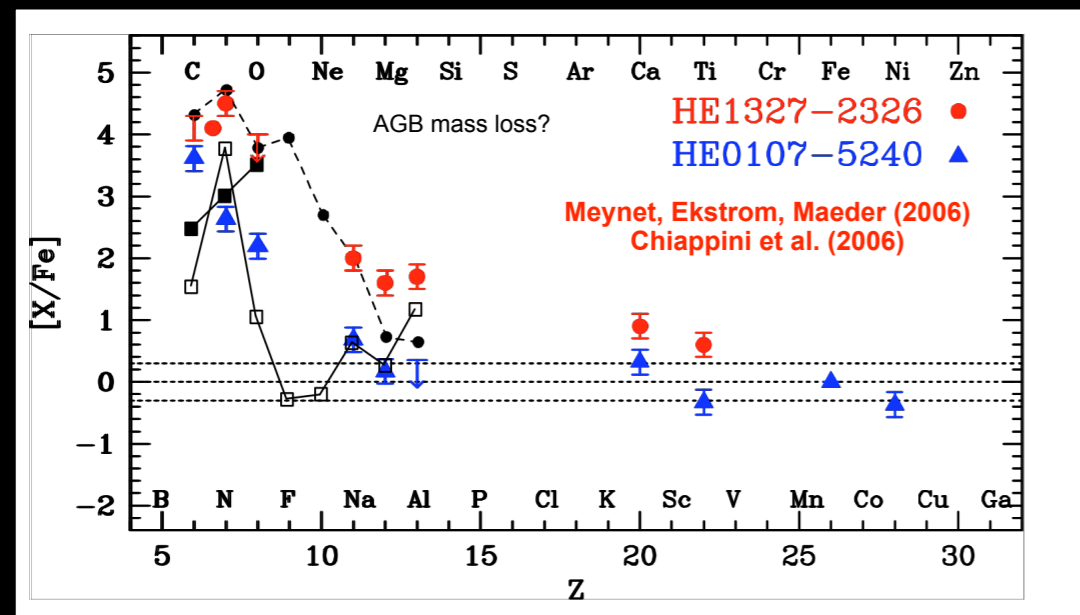


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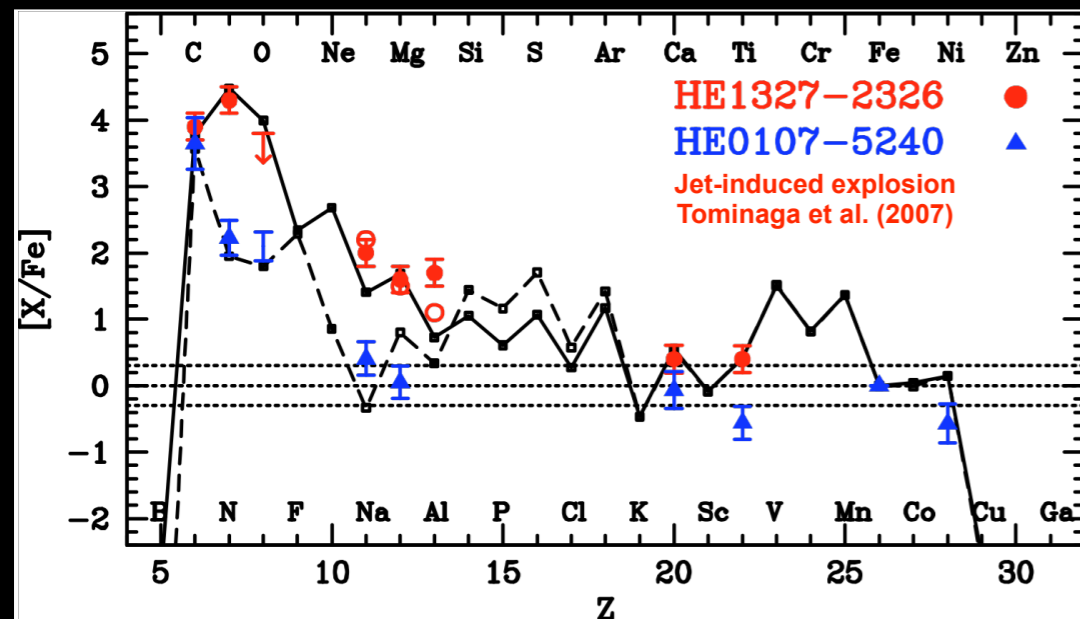
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Faint SNe in which light elements escape but heavy elements fall into the black hole? (Iwamoto et al. 2005)

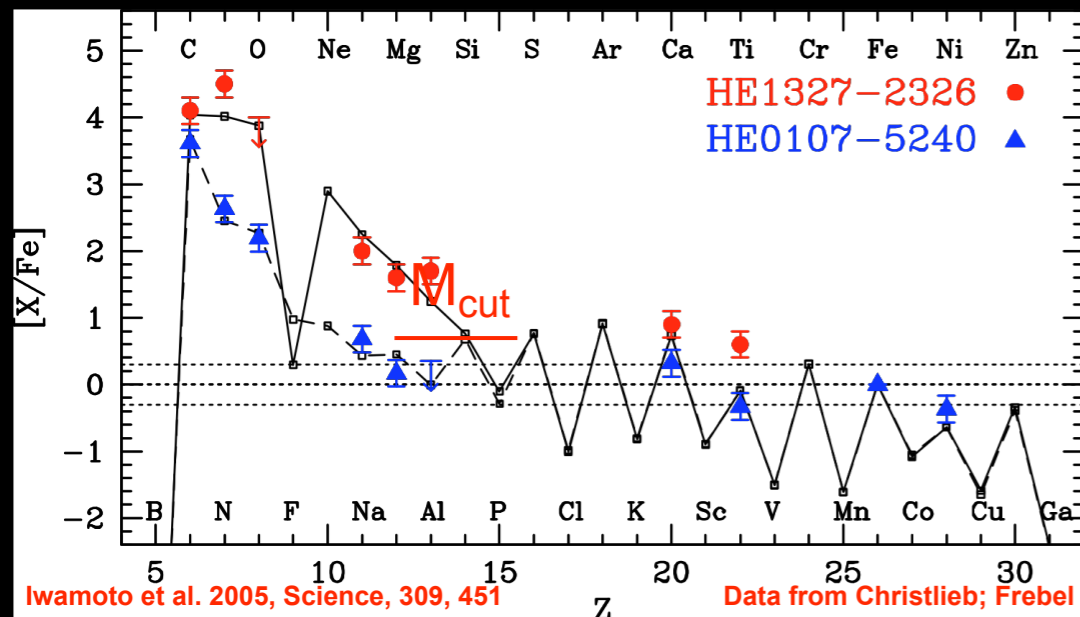


Stellar winds from rapidly rotating $Z = 0$ stars, or AGB mass loss?



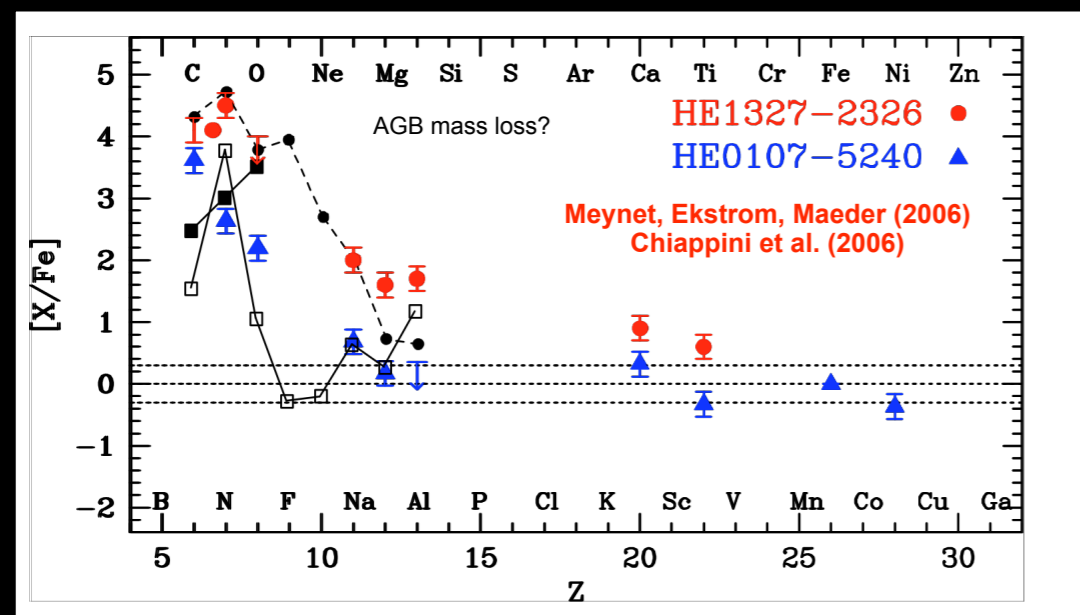
A jet-induced (GRB-like) explosion with mixing and fallback?

**Case Study 2:
The origins of the HMP stars**

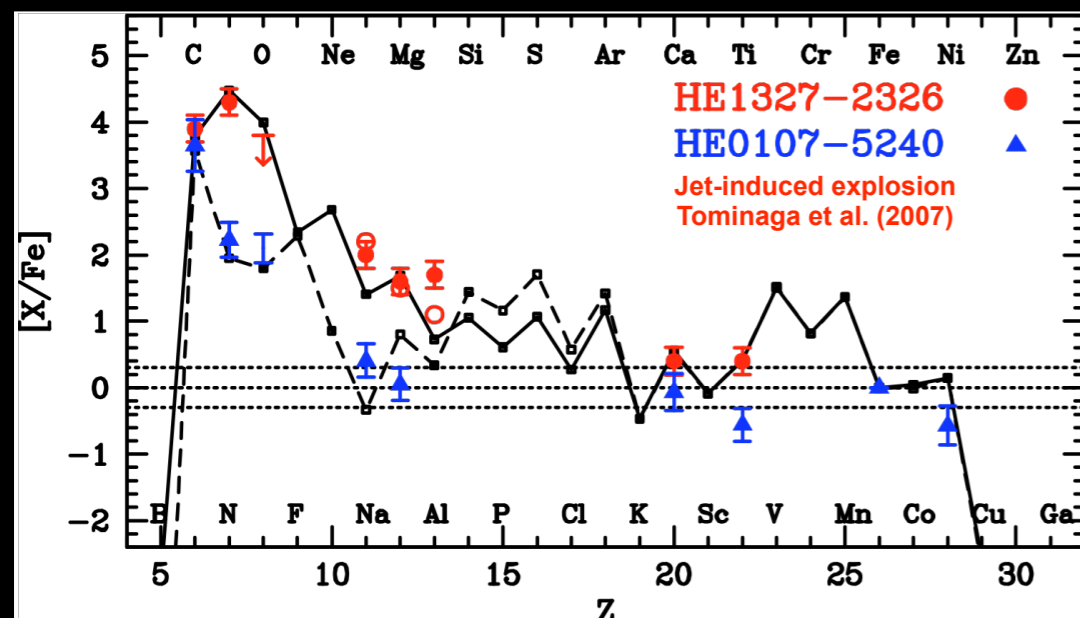


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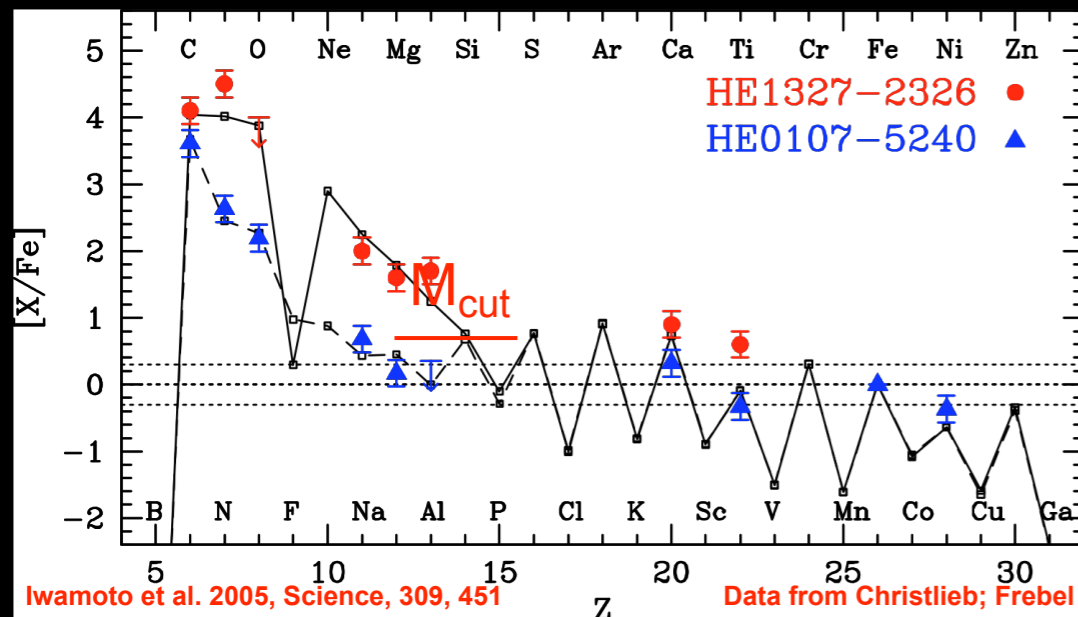


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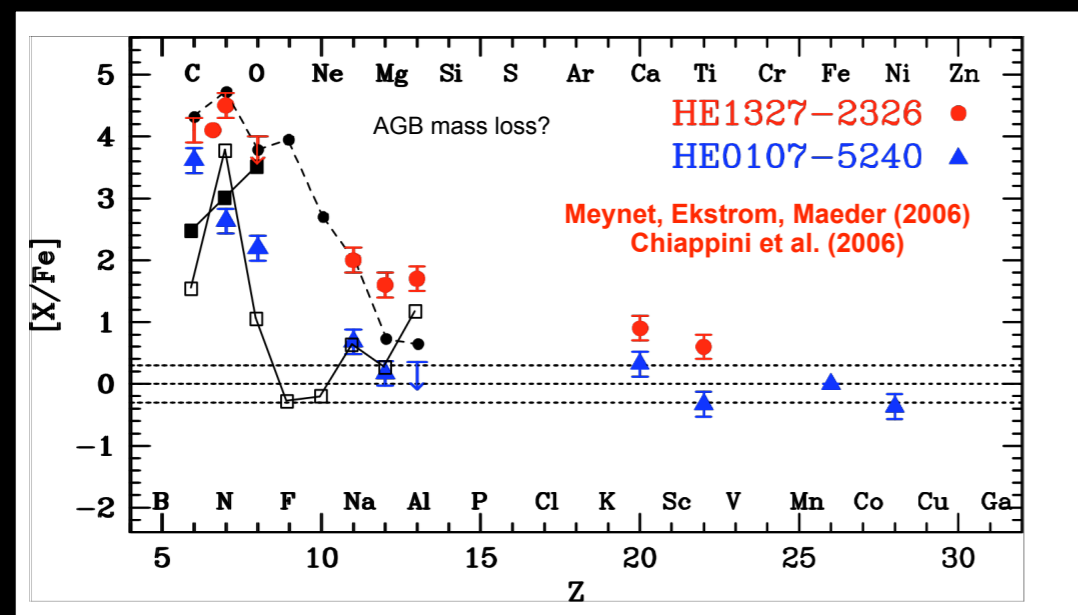
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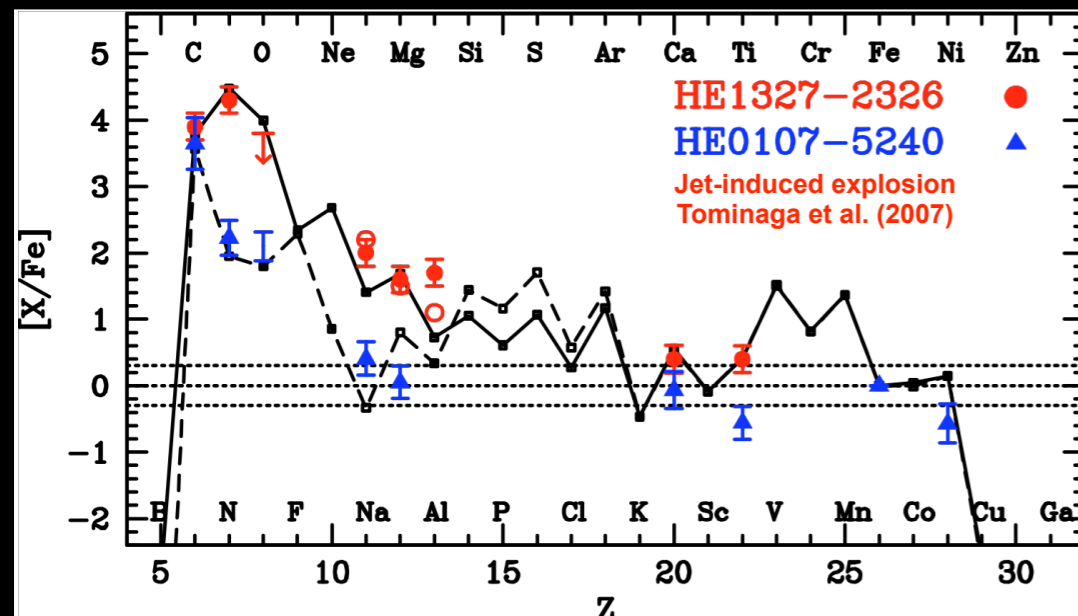
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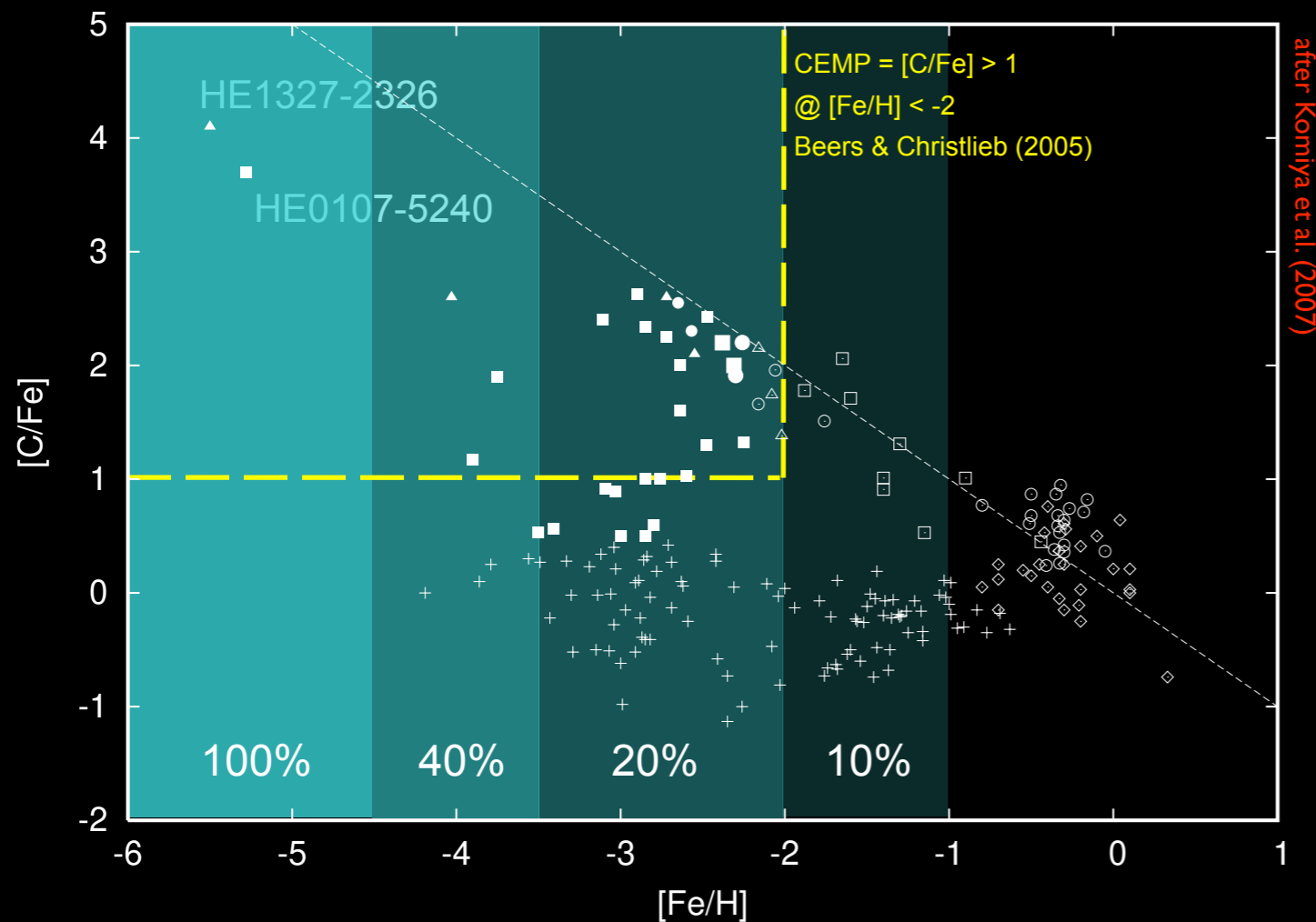
80% Ignorance: But instead of just a few uncertain parameters, we now have many competing mechanisms!



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



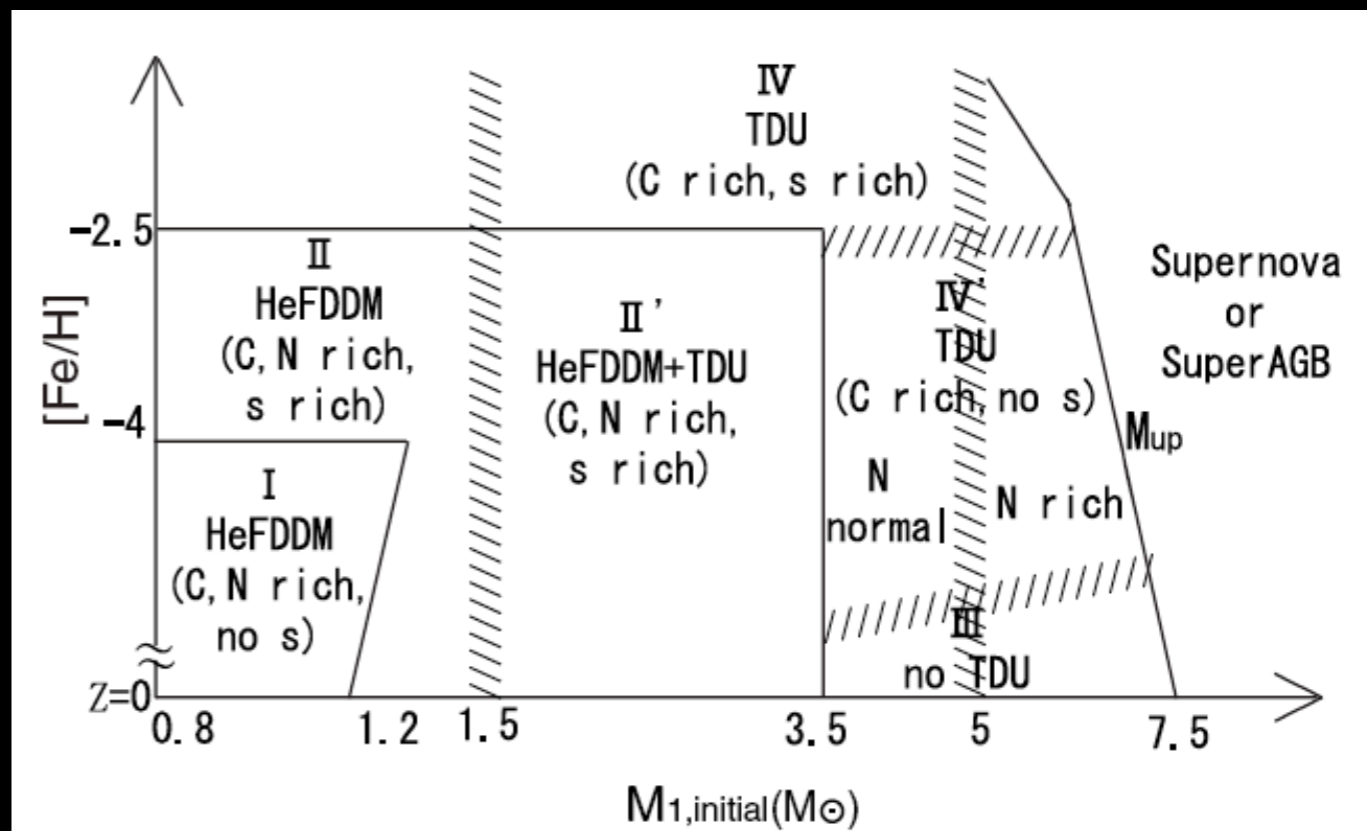
after Komiya et al. (2007)

The Carbon-Enhanced Metal-Poor Star Zoo

- CEMP
 - CEMP-no
 - CEMP-r
 - CEMP-s
 - CEMP-r/s
- 40% Progress

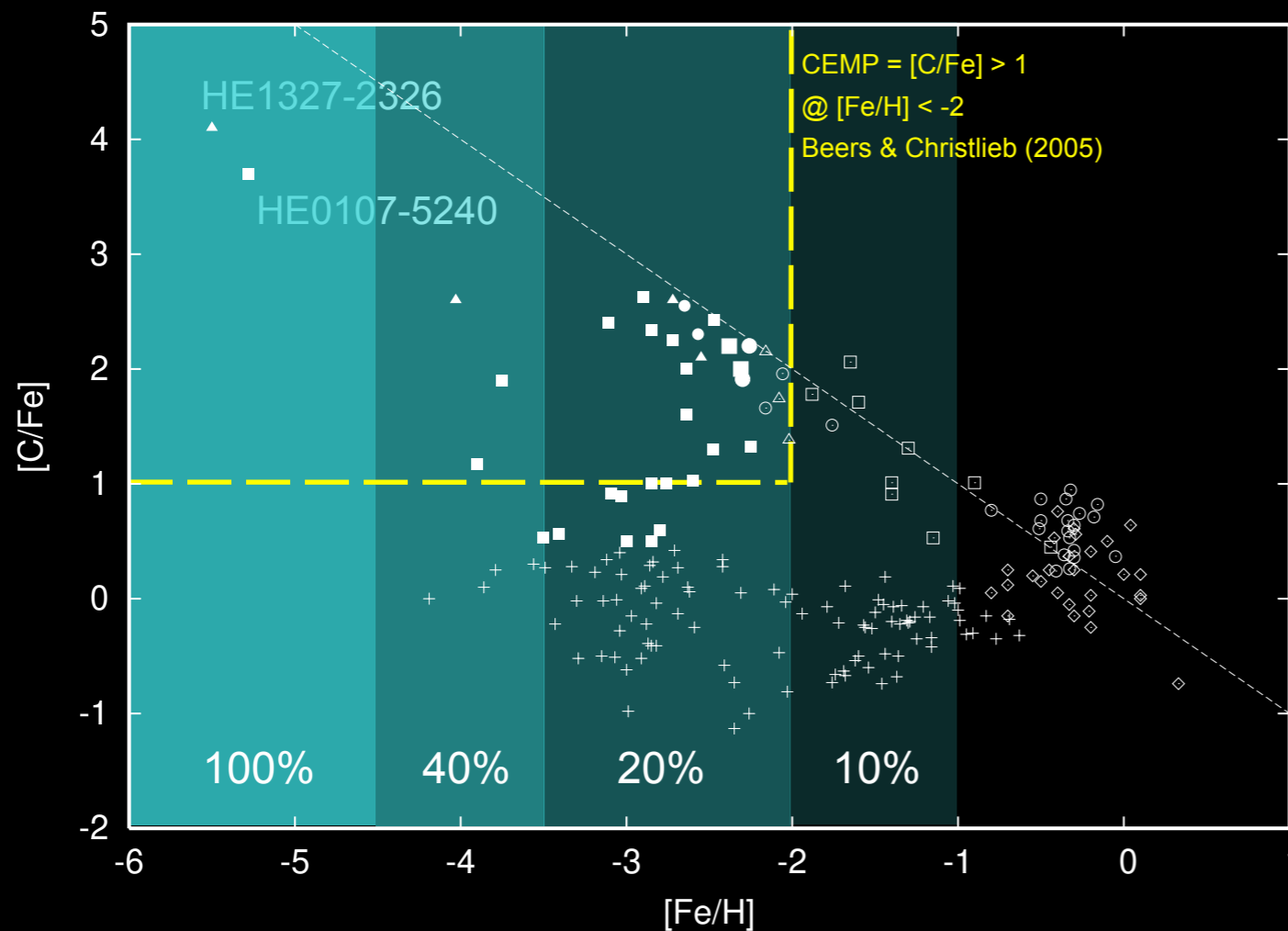
all these phenomena may relate to the mass- and-metallicity dependent yields of intermediate mass stars and AGB (Suda et al. 2006, Komiya et al. 2007, Masseron et al. 2009)

60% Ignorance



Illustration

Case Study 3: CEMP Zoo and AGB Nucleosynthesis



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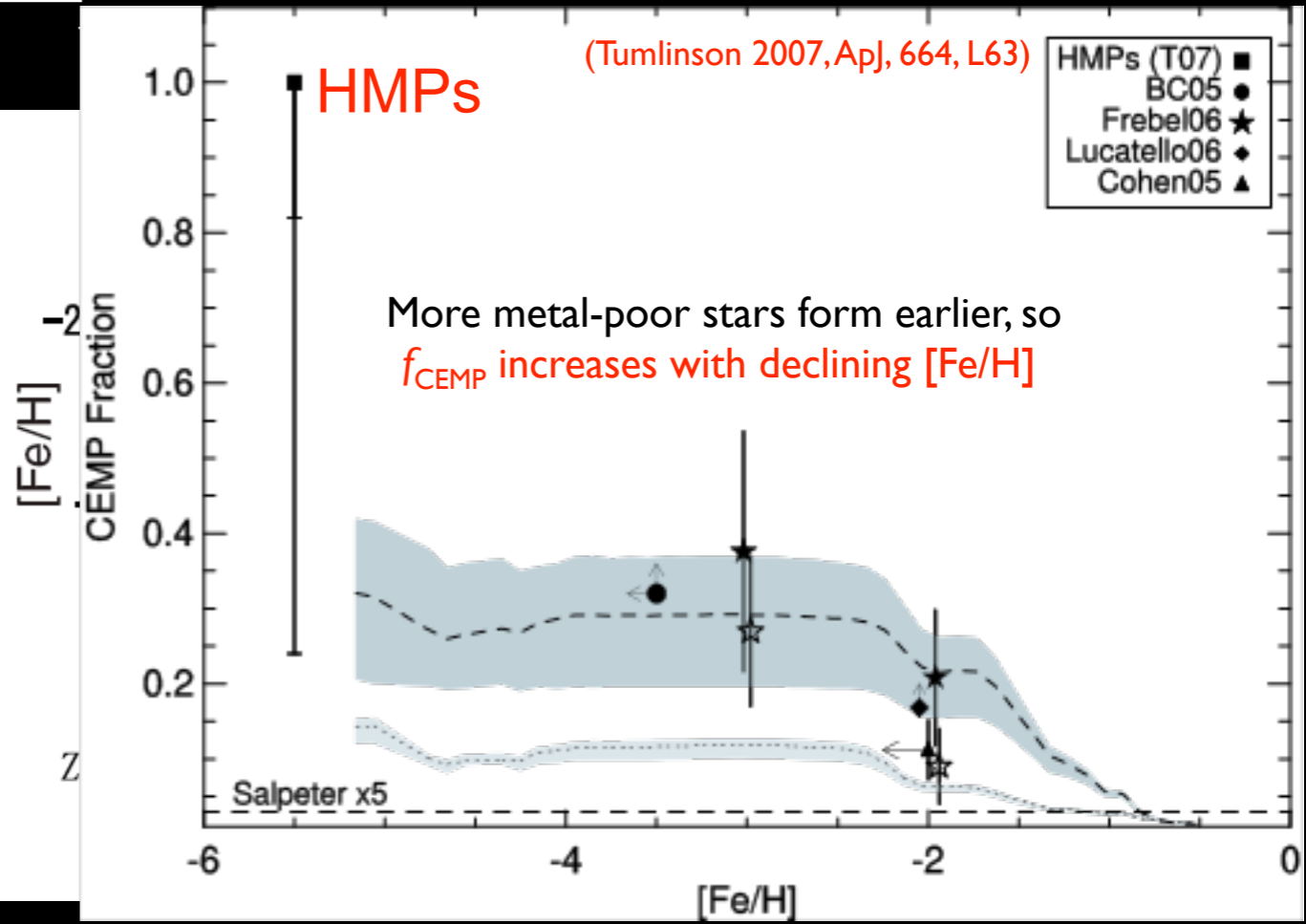
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60% Ignorance

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?

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

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



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

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. . . motivated our search of the fossil record

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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.

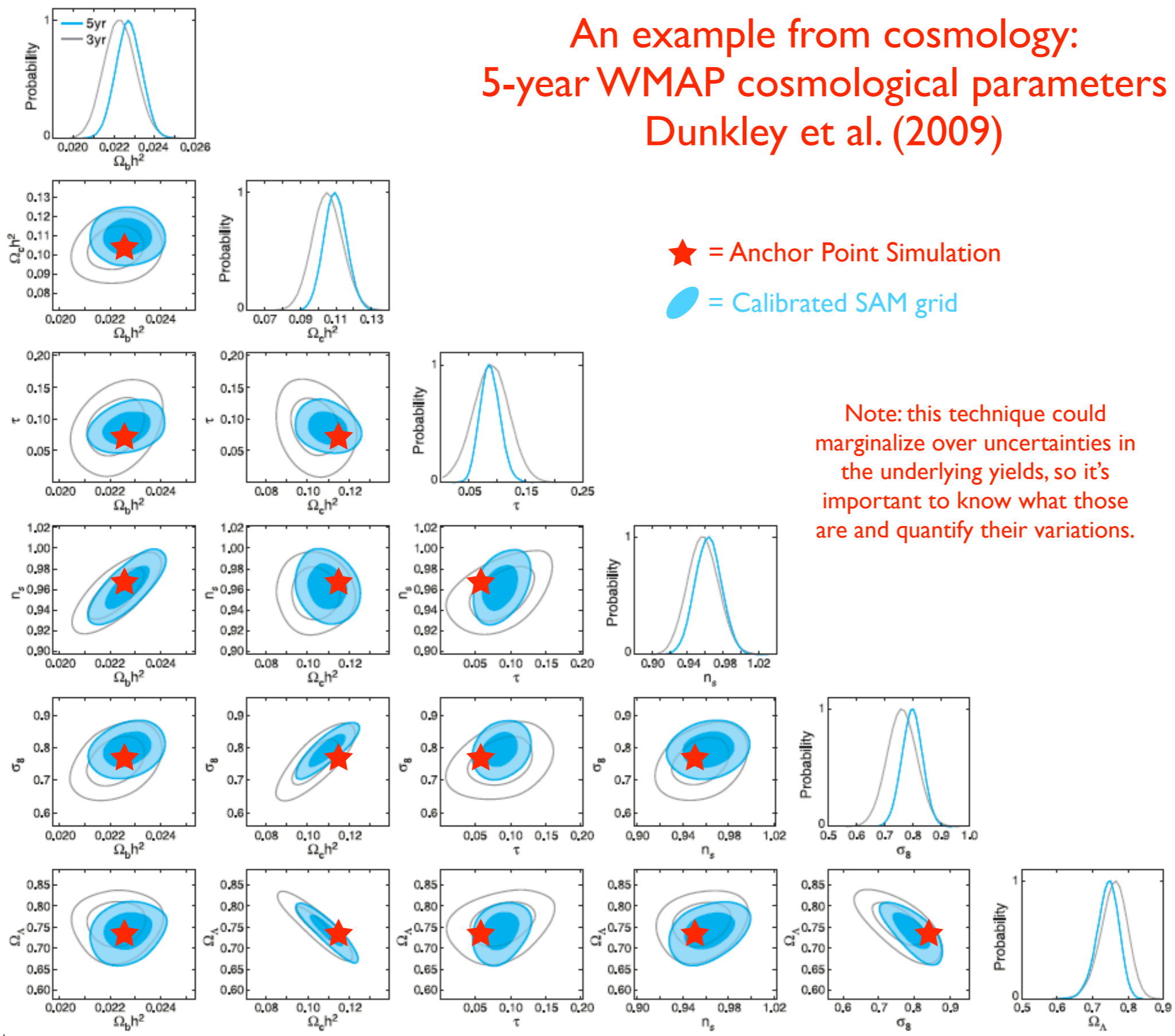
1) Unifying SAM and Numerical Models

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.

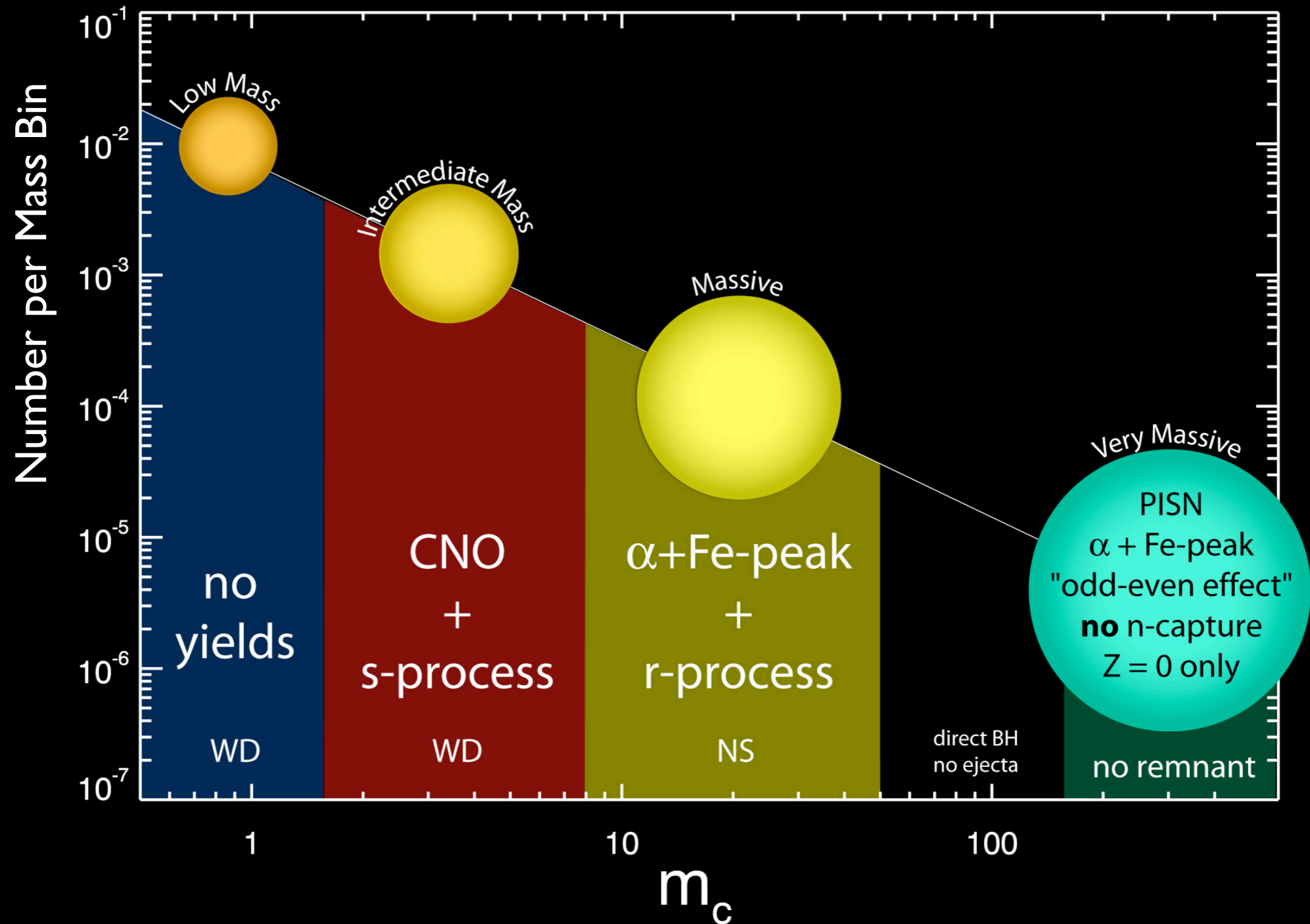
So SAMs still have a role, since for certain applications they can be calculated “on the fly”, and used to supply realistic stellar populations for much higher resolution Nbody simulations.

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

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

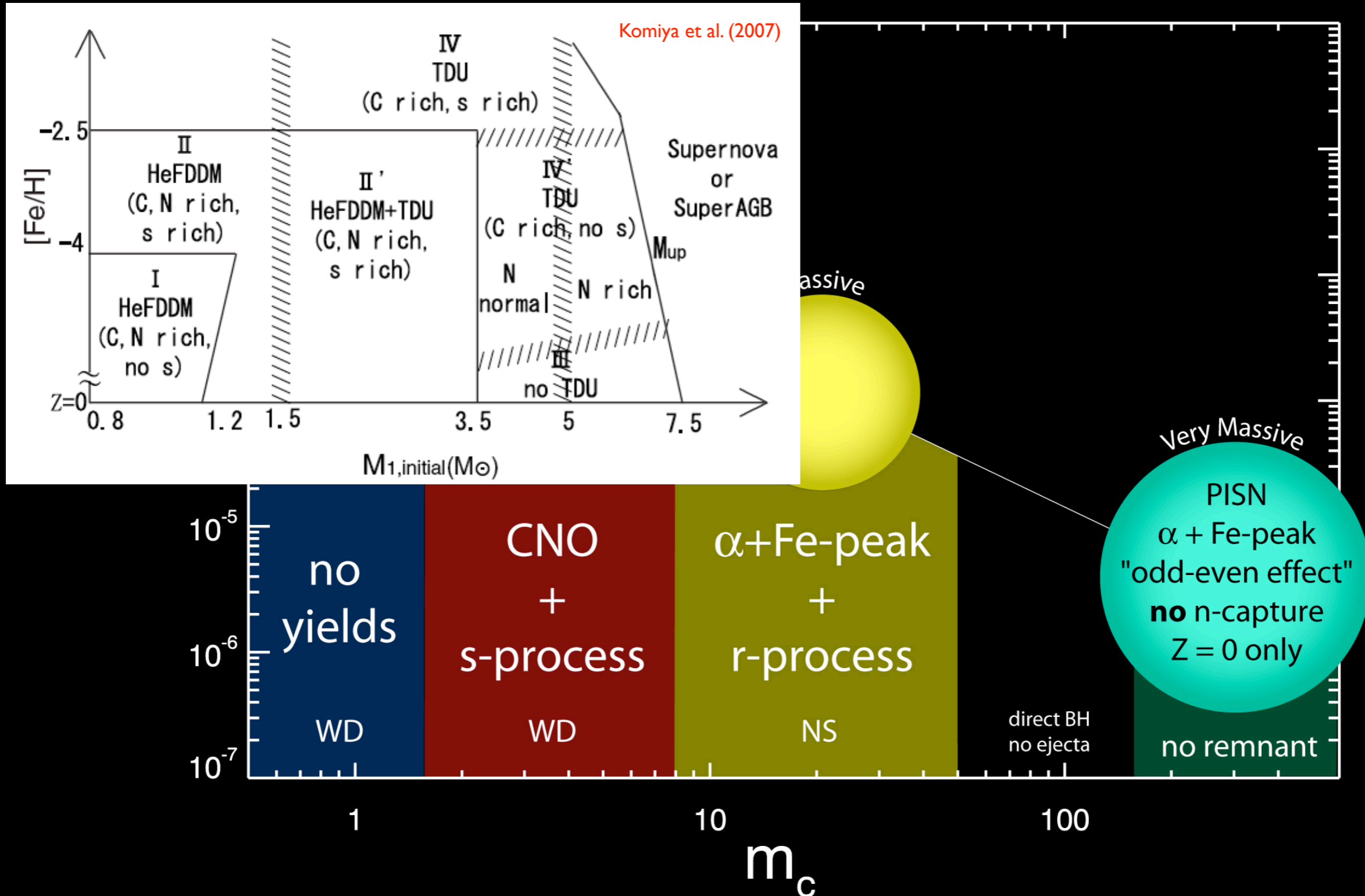


We would like to use robust and distinct signatures of stellar mass to diagnose IMF.



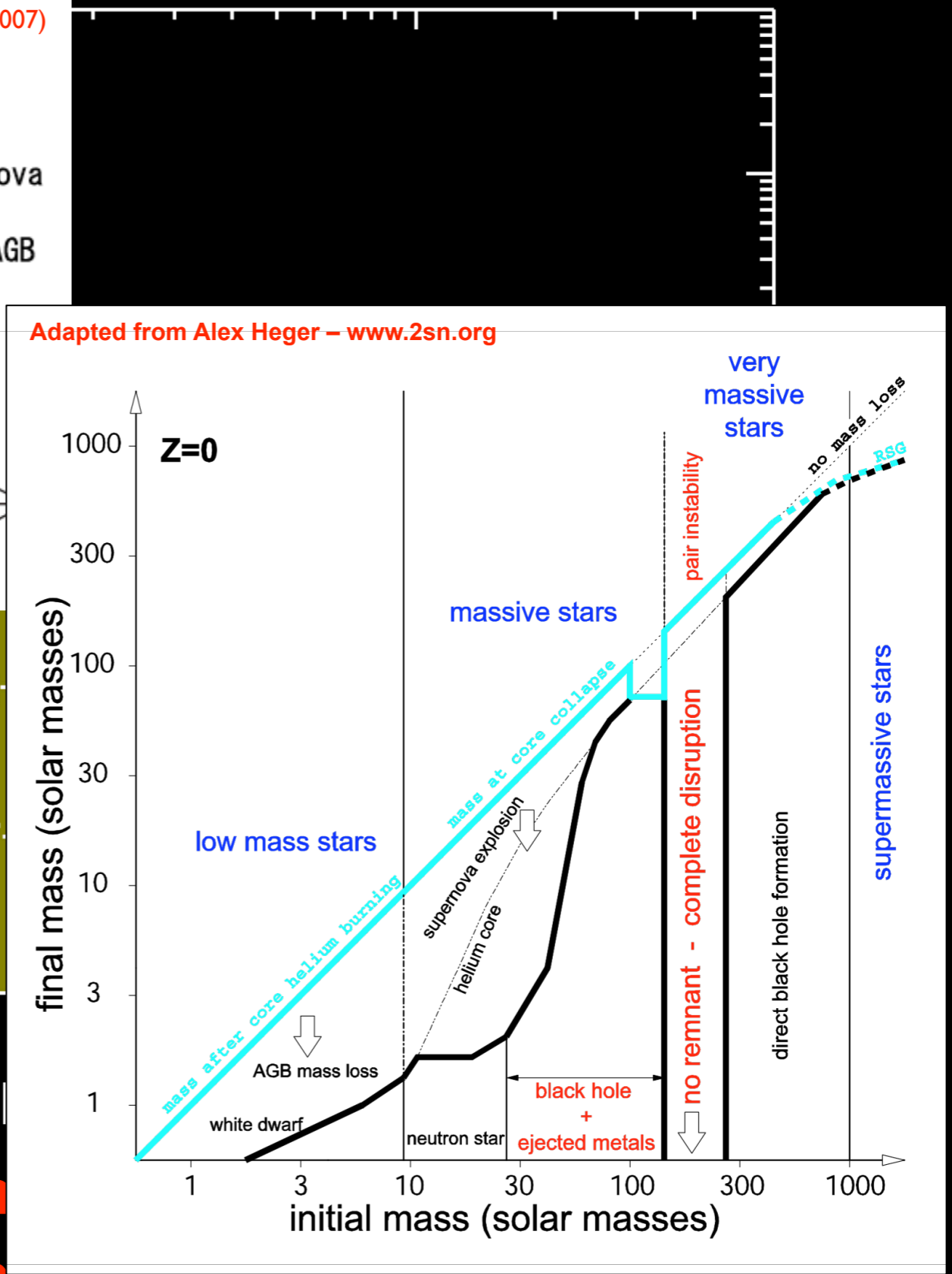
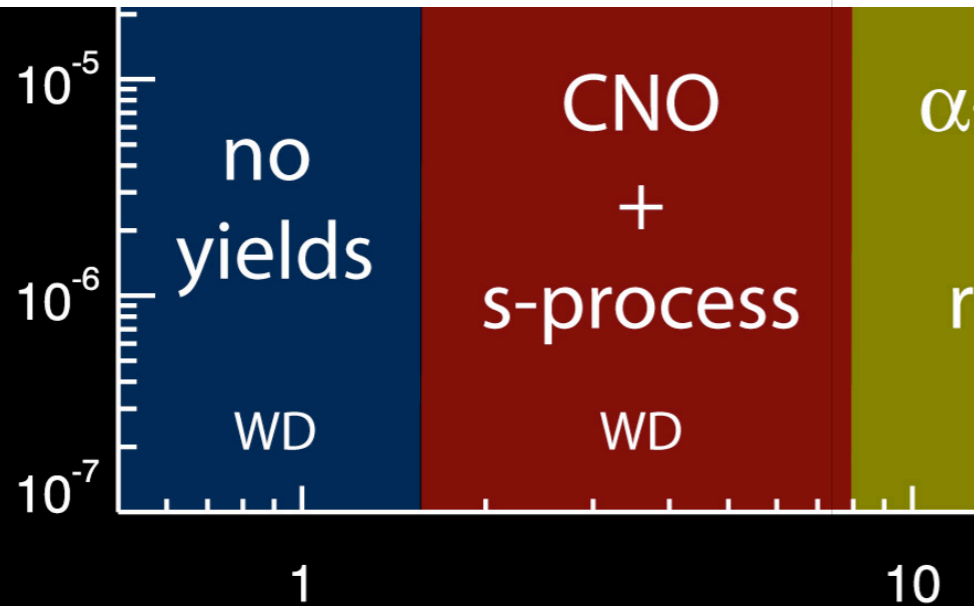
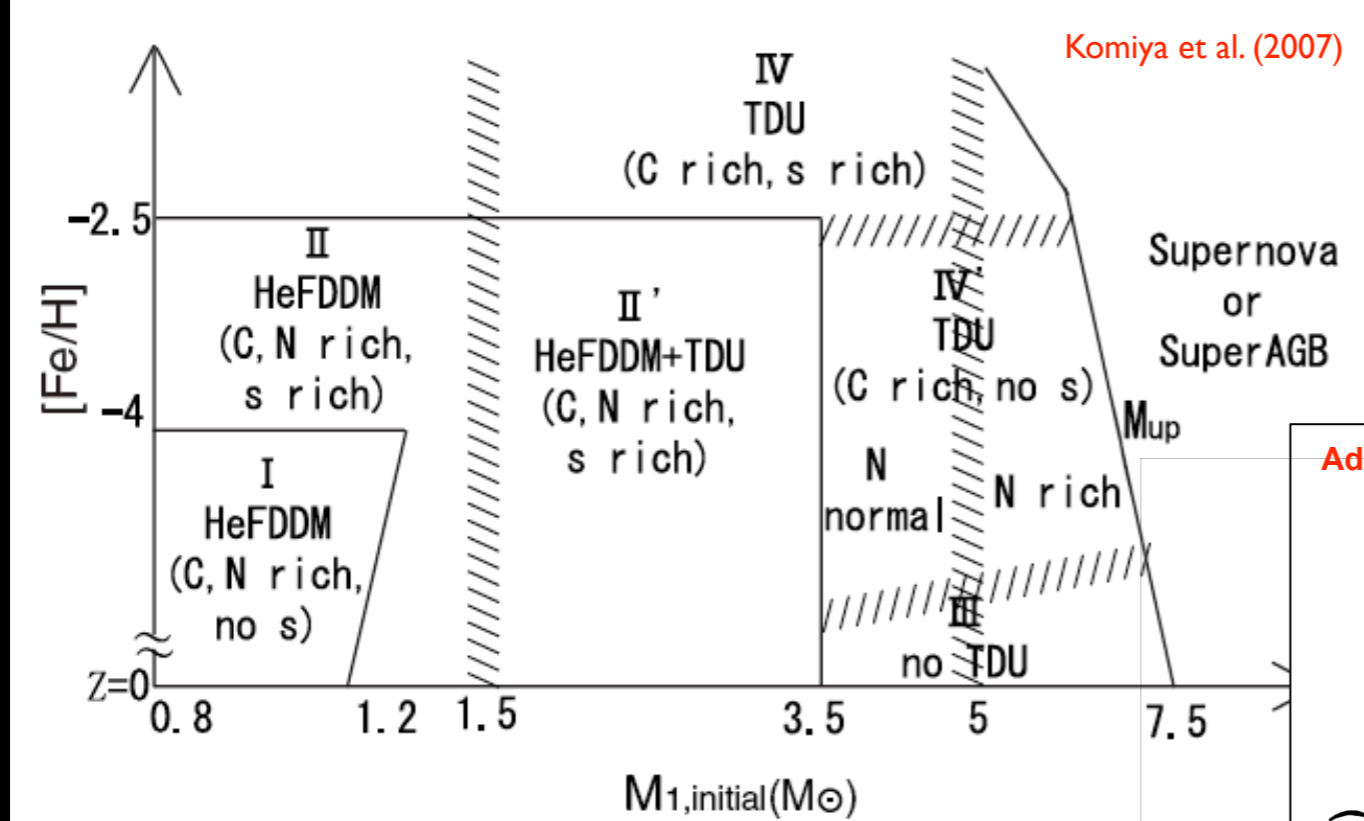
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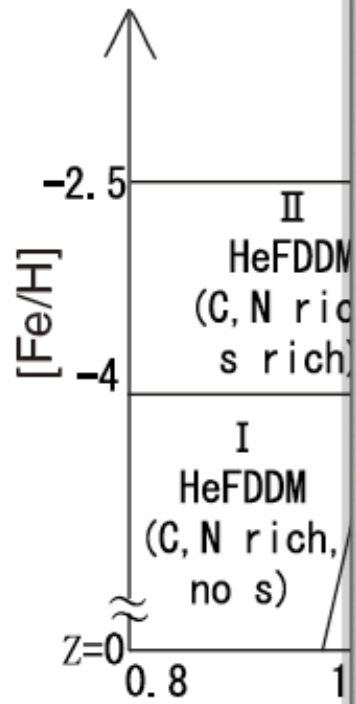
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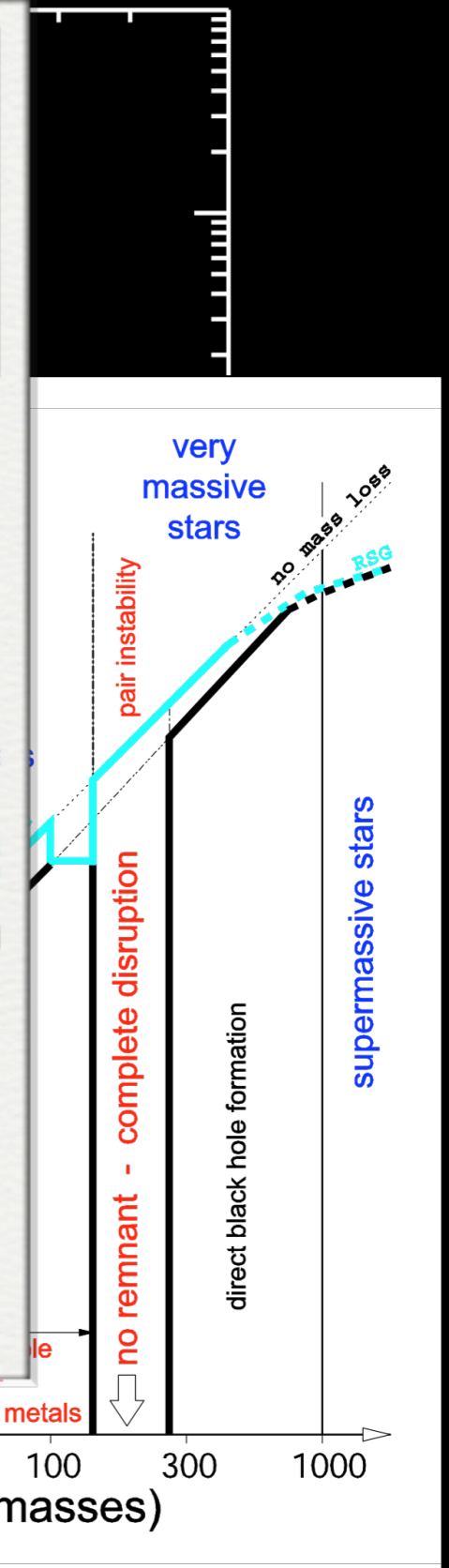
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We would like to use robust and distinct signatures of stellar mass to diagnose IMF.



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

<http://www.us-vo.org/>



Welcome to the New NVO Home Page! We welcome your **feedback** on the new site.

Discover, retrieve, and analyze astronomical data from archives and data centers around the world.

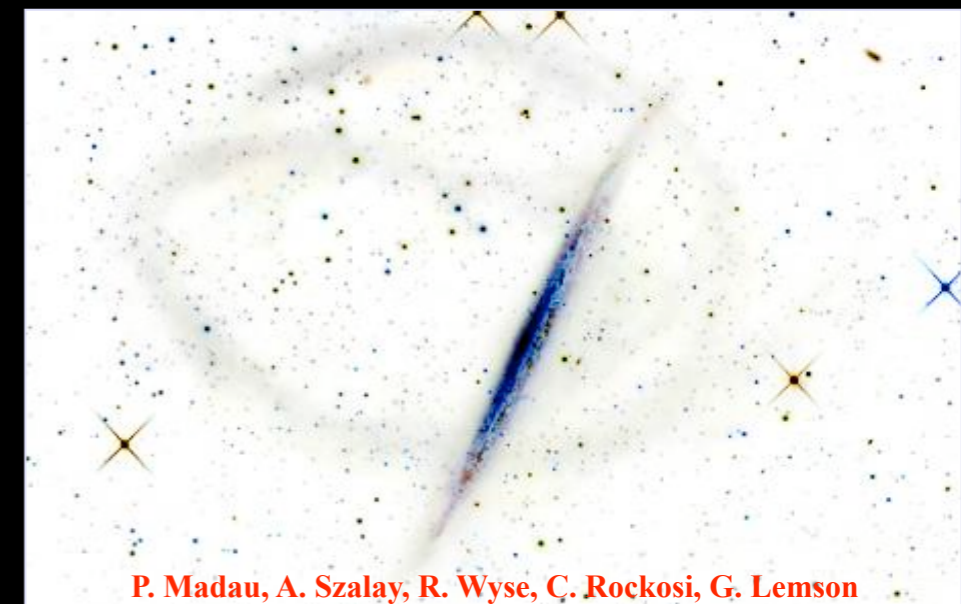
-  Need help? Not sure how to start?
» [Getting Started with NVO](#)
-  Collect all data at a given position.
» [DataScope](#)
-  Count matches between catalog entries and given positions.
» [Inventory](#)
-  Query databases and cross-match object lists
» [Open SkyQuery](#)
-  Find data collections and catalogs by searching their descriptions.
» [Directory](#)
-  Integrate data from multiple positions and datasets.
» [VIM](#)
-  Query the VO from the command line.
» [VO-CLI](#)
-  Convert text tables to the VOTable format used by VO applications.
» [Table Tools](#)
-  Do more with NVO.
» [Data Analysis & More](#)

The Virtual Astronomical Observatory (VAO):

- 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.

The Milky Way Laboratory (MWL, SantaCruz + Johns Hopkins):

- 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).

Are you Lonely

Working On Your Own?

HATE MAKING DECISIONS?

HOLD A MEETING

YOU CAN

- * SEE PEOPLE
- * DRAW FLOWCHARTS
- * FEEL IMPORTANT
- * IMPRESS COLLEAGUES

AND ALL ON COMPANY TIME !!!

MEETINGS

THE PRACTICAL ALTERNATIVE TO WORK

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.