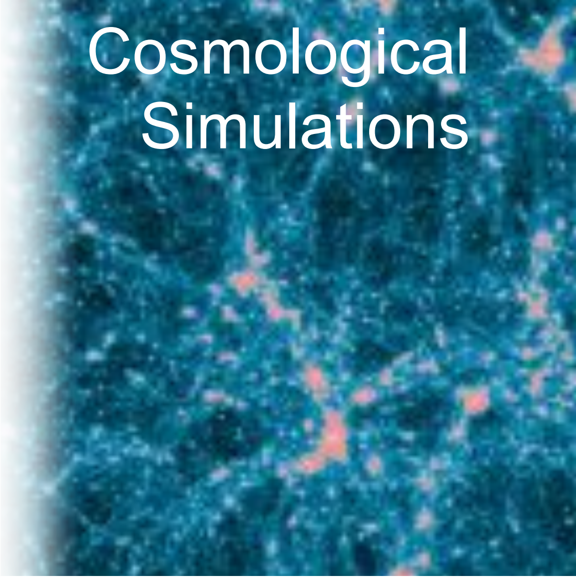
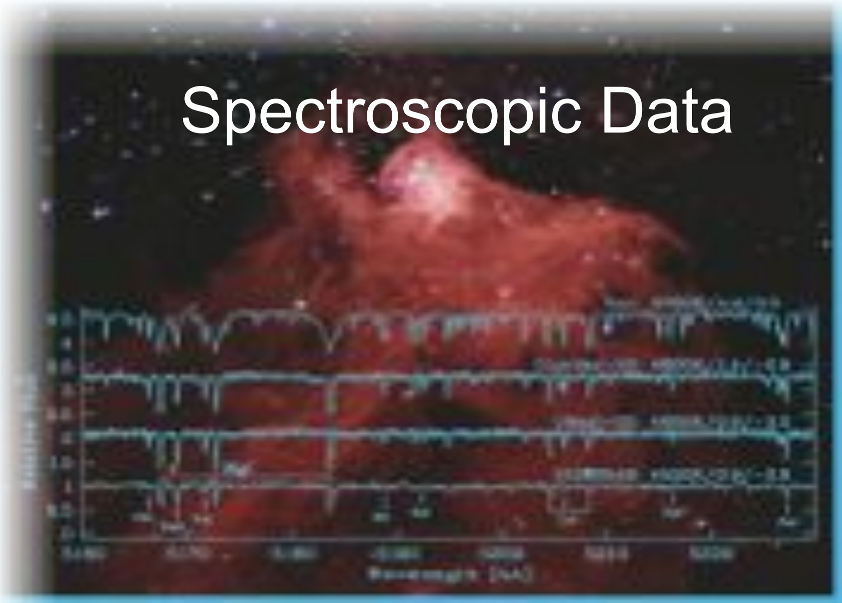
Stellar archaeology:

New science with old stars

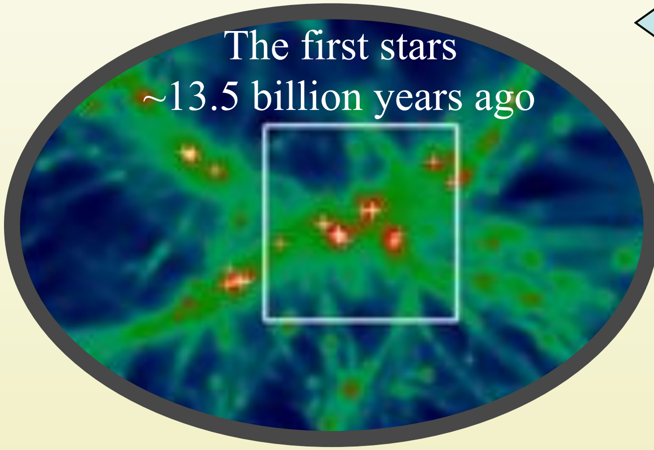


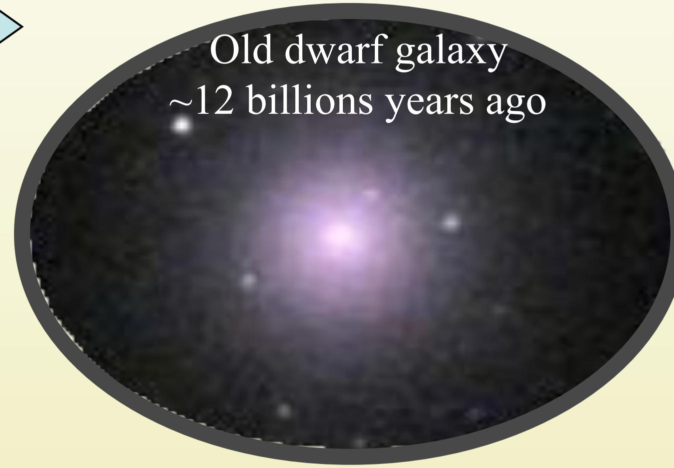
Anna Frebel



The Early Universe

The first heavy elements seed stars and galaxies





The chemical fingerprint of the early Universe is found in the oldest stars

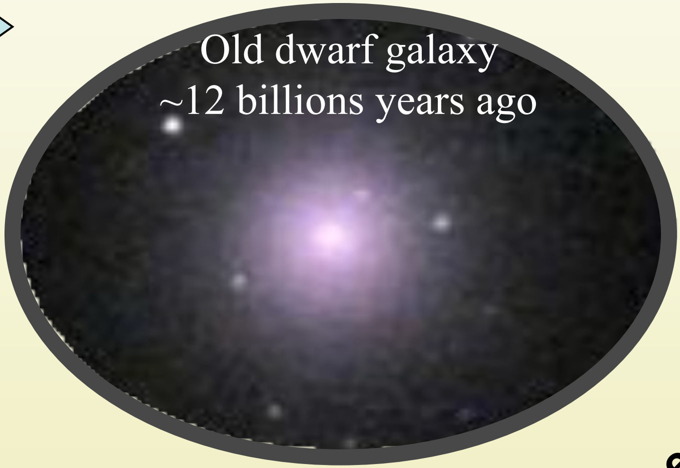
Chemical evolution proceeds; big stars explode soon, small stars live long

The Early Universe

The first heavy elements seed stars and galaxies

Stellar archaeology: Finding fossils of the earliest times

The most iron-poor stars with [Fe/H]<–5.0



The chemical fingerprint of the early Universe is found in the oldest stars

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The first heavy elements seed stars and galaxies

Stellar archaeology: Finding fossils of the earliest times

The most iron-poor stars with [Fe/H]<–5.0

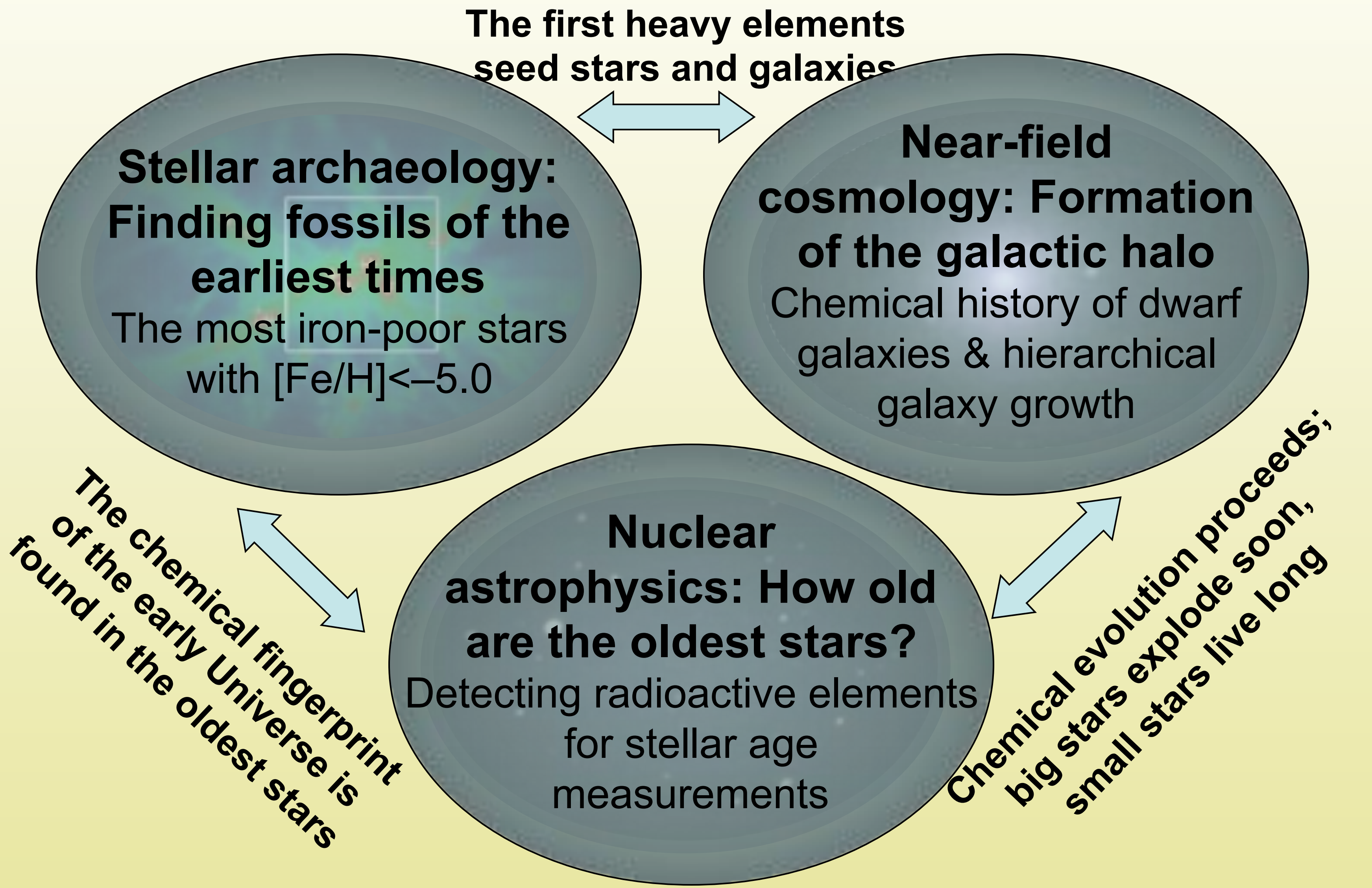
The chemical fingerprint of the early Universe is found in the oldest stars

Nuclear astrophysics: How old are the oldest stars?

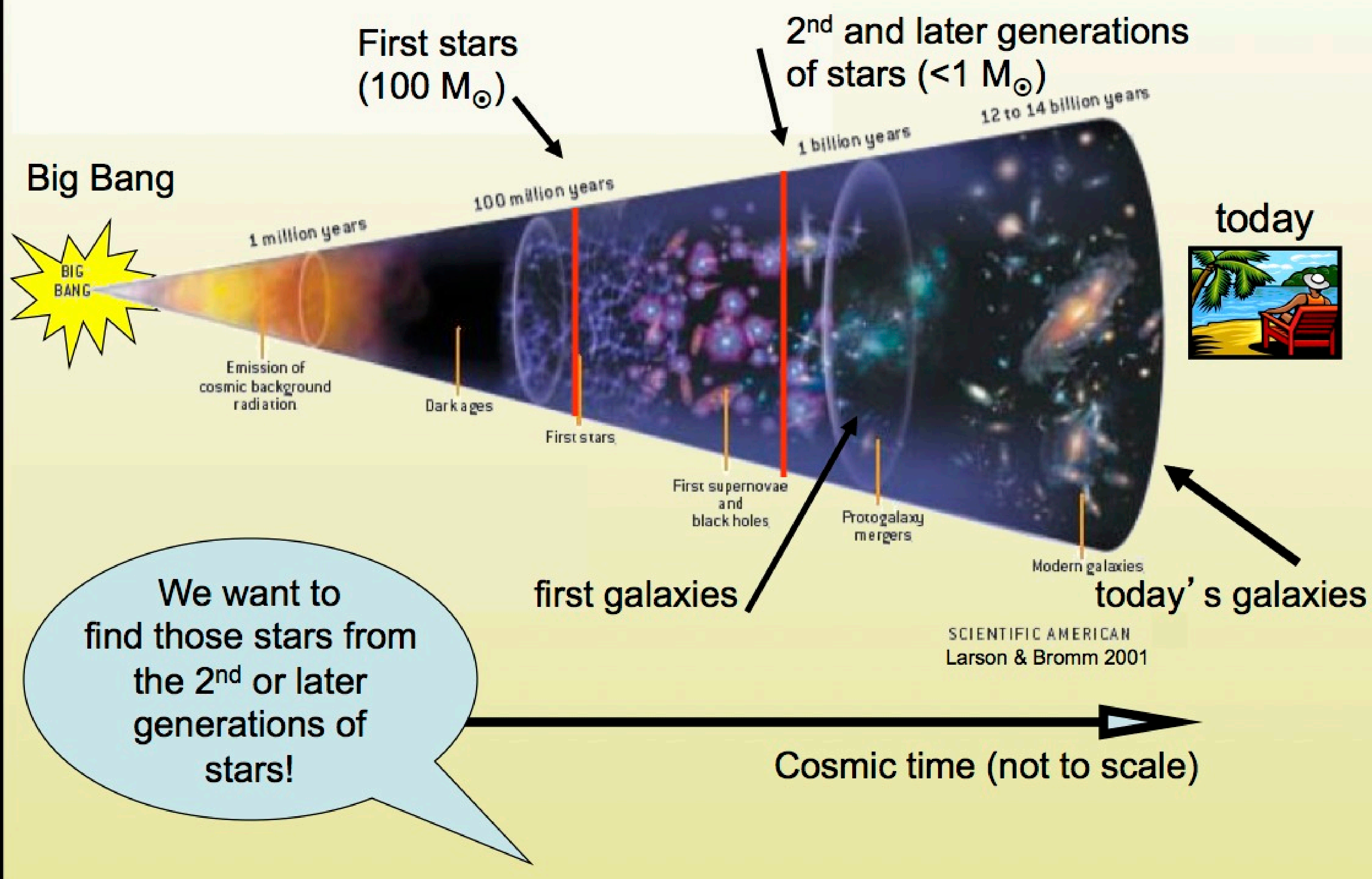
Detecting radioactive elements for stellar age measurements

Chemical evolution proceeds; big stars explode soon, small stars live long

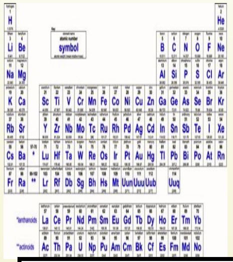
The Early Universe

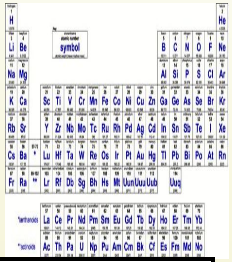


A LONG TIME AGO...



ASTRONOMER'S PERIODIC TABLE





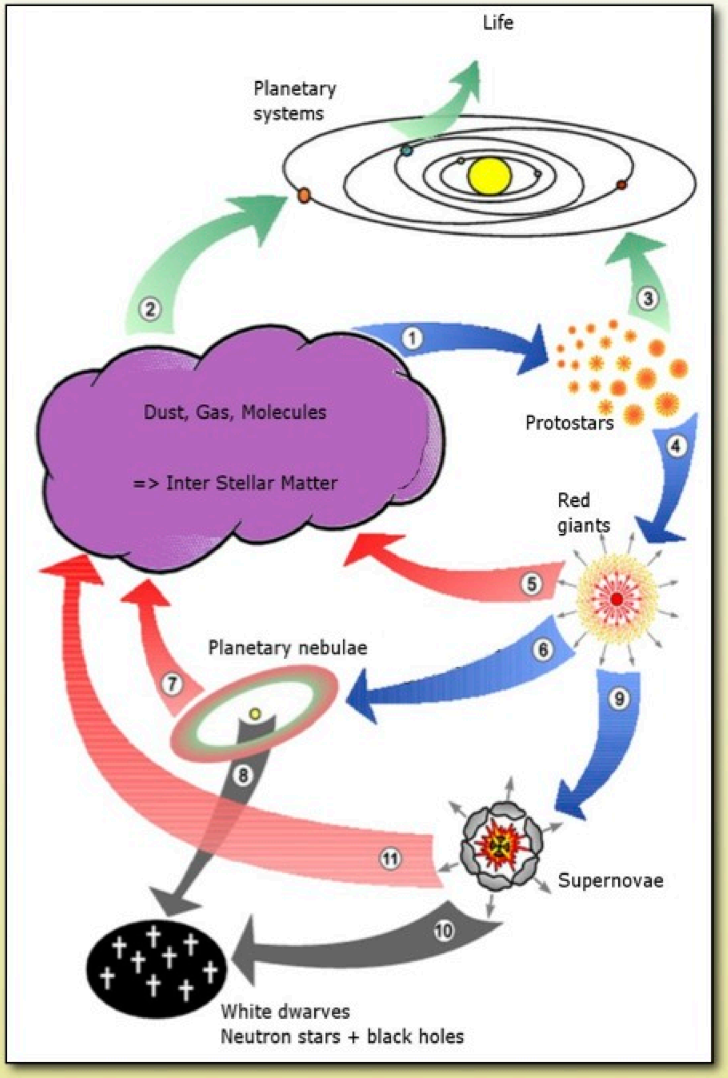
AF's view of the Universe:

Interesting ≡ 1 / metallicity

Metals Z

[Fe used to trace metallicity Z]

CHEMICAL EVOLUTION



Zentrum fuer Astronomie und Astrophysik, TU Berlin

All the atoms (except H, He & Li) were created in stars!

Pop III: zero-metallicity stars
Pop II: old halo stars
Pop I: young disk stars

Old stars contain fewer elements (e.g., iron) than younger stars

We look for the stars with the **least amounts** of elements heavier than H and He (= extreme Pop II stars)!

Finding the needle in the Haystack

Old stars from the early Universe are extremely rare!

What can we learn from old halo stars?

Low-mass stars (M < 1 M⊙)
⇒ Lifetimes > 10 billion years => still around!

Using metal-poor stars to reconstruct:

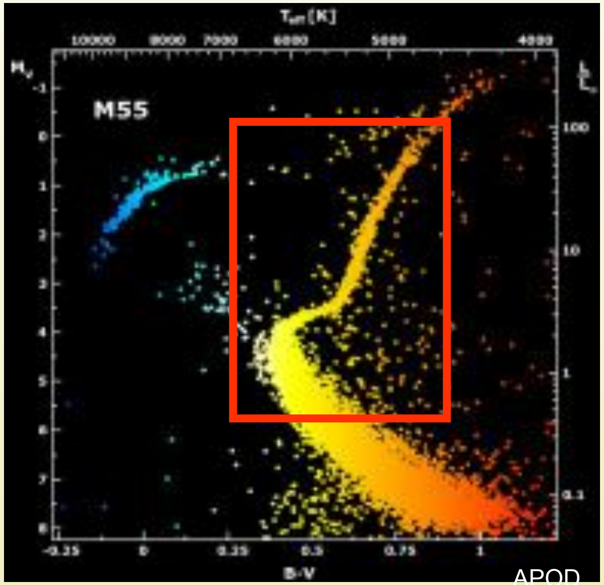
✓Origin and evolution of chemical elements
✓Relevant nucleosynthesis processes + sites
✓Chemical + dynamical history of the Galaxy
✓Lower limit to the age of the Universe

... and to provide constraints

✓Nature of the first stars & initial mass function
✓Early star & early galaxy formation processes
✓Nucleosynthesis & chemical yields of first/early SNe
✓Hierarchical assembly of galaxies & halo formation

Hertzsprung-Russell-Diagram

Luminosity

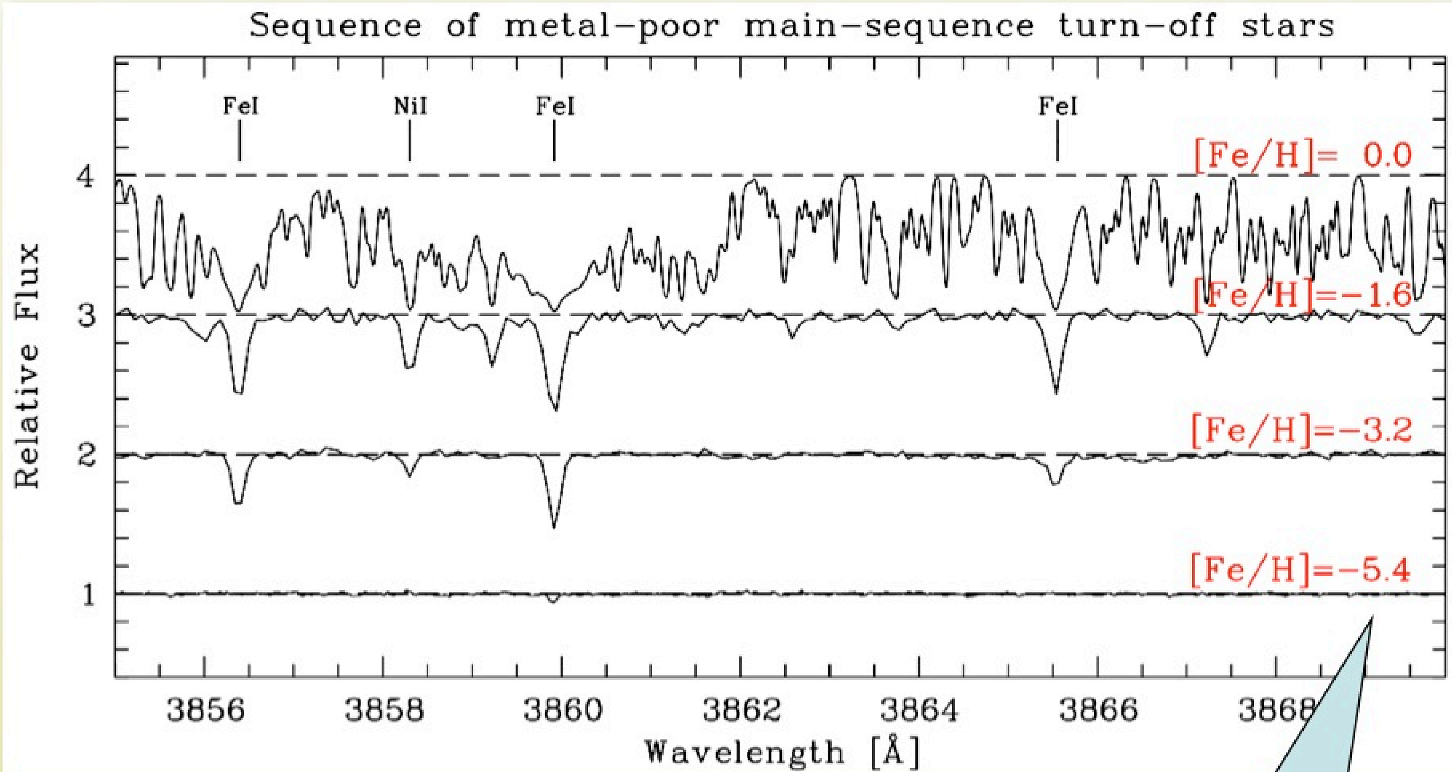


Temperature

> ***Metal-poor stars are a great tool for near-field cosmology because they are the local equivalent of the high-redshift Universe!***

Taking a spectroscopic look

"Look-back time"



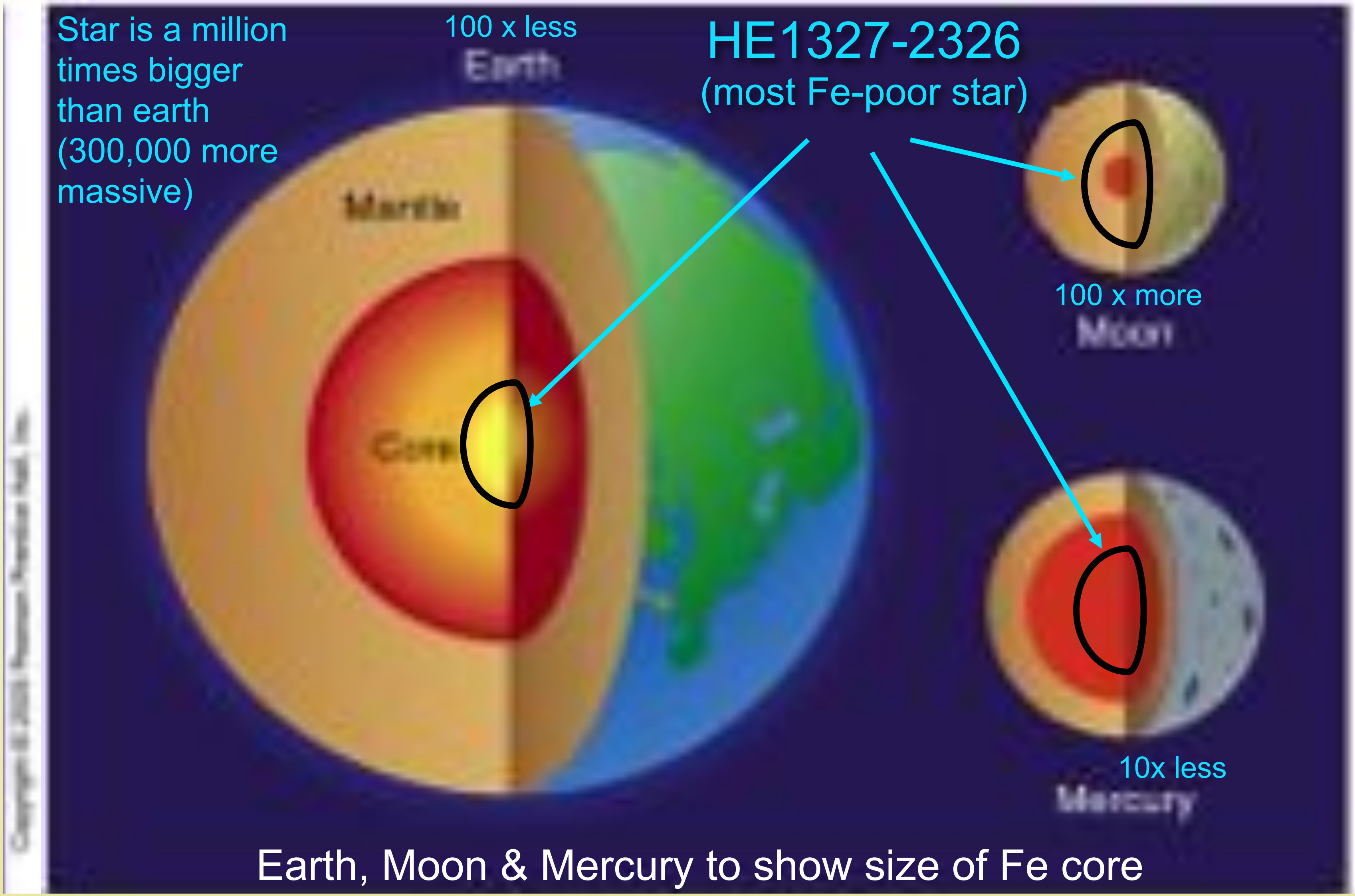
Galactic chemical evolution

Abundances are derived from integrated absorption line strengths

$[Fe/H] = \log(N_{Fe}/N_H)_* - \log(N_{Fe}/N_H)_\odot$

equals 1/250,000th of the solar Fe abundance

How much iron is in there?



CLASSIFICATION SCHEME

Range	Term	Acronym	#
[Fe/H] ≥ +0.5	Super metal-rich	SMR	some
[Fe/H] = 0.0	Solar	—	a lot!
[Fe/H] ≤ –1.0	Metal-poor	MP	very many
[Fe/H] ≤ –2.0	Very metal-poor	VMP	many
[Fe/H] ≤ –3.0	Extremely metal-poor	EMP	~150
[Fe/H] ≤ –4.0	Ultra metal-poor	UMP	1
[Fe/H] ≤ –5.0	Hyper metal-poor	HMP	2
[Fe/H] ≤ –6.0	Mega metal-poor	MMP	--

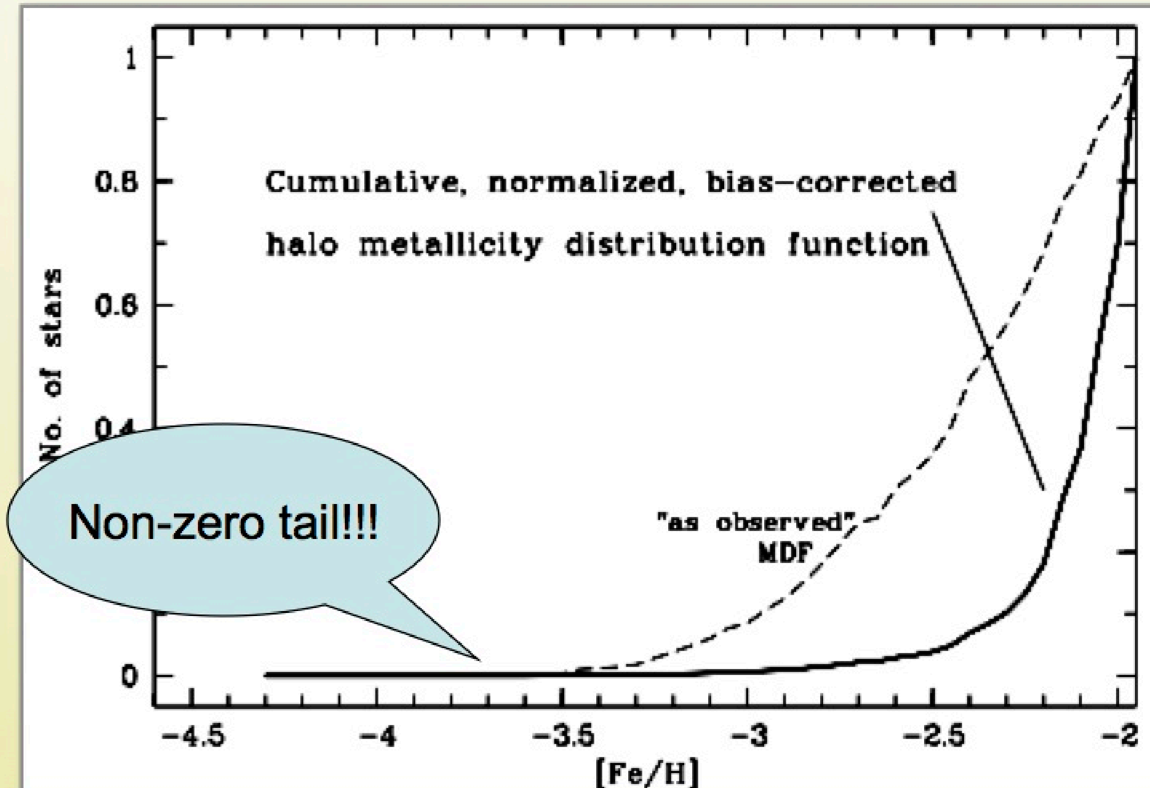
Extreme Pop II stars!

as suggested by Beers & Christlieb 2005

HALO METALLICITY DISTRIBUTION FUNCTION (MDF)

'As observed' raw MDF is **not** a realistic presentation!

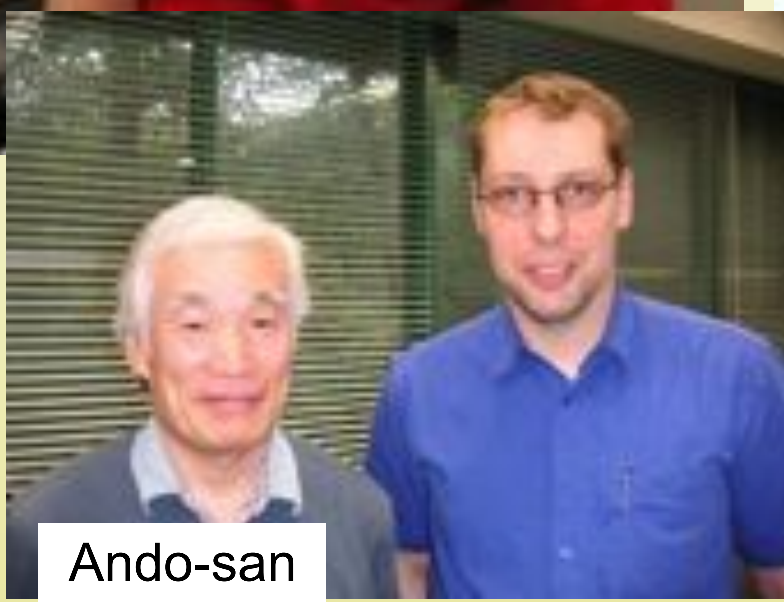
But shows that we have been doing a good job in finding these stars..!



Schoerck et al. 2008

In 2004 (@ NAOJ)

Norbert Christlieb



Ando-san

Aoki-san

Japanese 8m Subaru telescope @ Mauna Kea, Hawaii

May 30, 2004:
First Subaru/HDS observation of HE 1327-2326
by Aoki Wako (NAOJ)

The most iron-deficient stars known

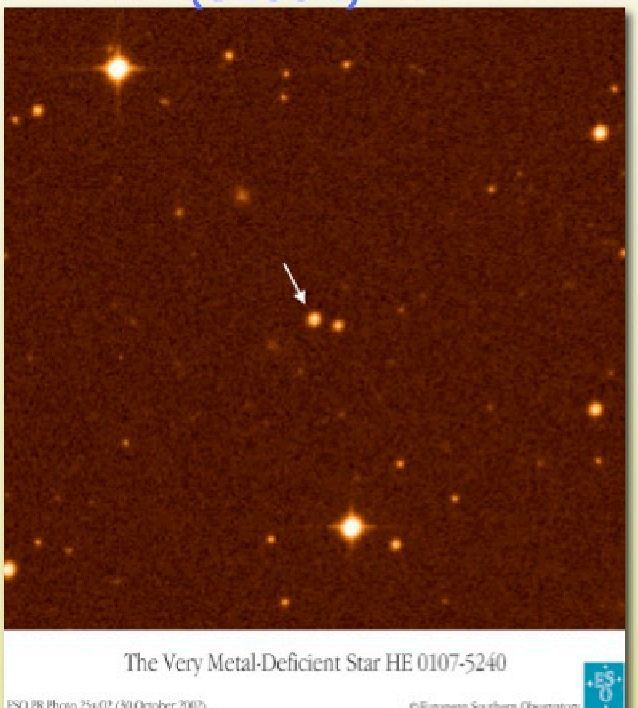
HE 0107-5240

Red giant
(5200K)

Masses: 0.6 - 0.8 $M_\odot$

HE 1327-2326

Subgiant
(6180K)



$[Fe/H]_{NLTE}$ = -5.2

Christlieb et al. (2002), Nature 419, 904
Christlieb et al. (2004), ApJ 603, 708
Bessell et al. (2004), ApJ 612, L61

$[Fe/H]_{NLTE}$ = -5.4

Frebel, Aoki et al. 2005, Nature 434, 871
Frebel et al. 2006, ApJ 638, L17
Aoki, Frebel et al. 2006, ApJ 639, 897
Frebel et al. 2008, ApJ 684, 588

Searching for the oldest stars

Release date:

August 2012 (in German)

To appear in English:
2013

aller unserer Forschungsaktivitäten geworden. Alles ging so schnell, dass ich kaum wahrnehmen konnte, dass dieser Stern einen entscheidenden Wendepunkt in meiner Arbeit herbeigeführt hatte. Zu dem damaligen Zeitpunkt gab es einen Stern, CD –38° 245, mit [Fe/H] = –4.0 (ein leicht korrigierter Wert gegenüber der Originalanalyse) und einen anderen, HE 0107-5240, mit [Fe/H] = –5.2. Alle anderen Sterne hatten höhere Eisenhäufigkeiten. Einen Stern mit einer Metallizität zwischen der dieser beiden Sterne zu finden, galt als sensationell. Denn andere Wissenschaftler hatten schon angefangen darüber zu spekulieren, ob es in dem großen Bereich zwischen [Fe/H]= –4 und [Fe/H] = –5 überhaupt Sterne geben könnte.

Jetzt war der Moment gekommen, in dem wir dringend ein hochaufgelöstes Spektrum benötigten, um die Metallizität zu bestätigen. Von Zufall konnte man schon gar nicht mehr sprechen: Denn nur einige Tage später sollte einer unserer japanischen Kollegen nach Hawaii zum 8 m Subaru-Teleskop fliegen, das mit einem hochauflösenden Spektrograph ausgestattet ist. Ziel seiner Beobachtungskampagne war die Suche nach extrem metallarmen Sternen – ein Programm, das schon seit einigen Jahren am Laufen war. Die Teleskopzeit war schon 2003 bewilligt worden, und so war es ein außerordentlich glückliches Zusammentreffen, dass ich genau zum Zeitpunkt dieser Beobachtungen diesen unglaublich guten Kandidaten gefunden hatte. Der japanische Kollege erklärte sich natürlich sofort dazu bereit, den Stern in das Programm aufzunehmen und ihm die höchste Priorität bei den Beobachtungen einzuräumen.

Was folgte, glich dem Leben auf der Überholspur – zumindest wissenschaftlich gesehen. Wir bekamen das hochaufgelöste Spektrum, und tatsächlich – HE 1327-2326 war rekordverdächtig metallarm! Denn wie sich herausstellte, hatten wir seine Eisenhäufigkeit überschätzt. Interstellares Kalzium zwischen uns und dem Stern war im Spektrum deutlich zu erkennen, was aber im Nachbeobachtungsspektrum aufgrund der geringeren Auflösung nicht hatte erkannt werden können. In Wirklichkeit hatte der Stern viel weniger Kalzium zu bieten. Da wir jetzt aber zwei winzig kleine Eisenlinien im hochaufgelösten Spektrum sehen konnten, waren wir nicht mehr auf die Abschätzung der Metallizität mit Hilfe der Kalziumlinie angewiesen.

Insgesamt konnten wie nur vier Eisenlinien im ganzen Spektrum detektieren, da der Stern aufgrund seines enormen Eisendefizits fast gar kein Eisen in sich hat und die warme Sterntemperatur das Erscheinen der Linien zusätzlich verringerte. Trotzdem konnten wir so die Eisenhäufigkeit von HE 1327-2326 bestimmen: [Fe/H] = –5.4, was nur einem Zweihundertfünfzigtausendstel der solaren Eisenhäufigkeit entspricht. Ich hatte den neuen Rekordhalter für den eisenärmsten Stern in meiner Stichprobe noch im ersten Jahr meiner Doktorarbeit gefunden. Abbildung 10.4 zeigt einen Teil des hochaufgelösten Spektrums mit der Kalzium K-Linie sowie der stärksten Eisenlinien.

Ich konnte das alles kaum glauben, auch wenn meine Arbeit ja genau auf ein solches Ereignis abgezielt hatte. Schon in der groben Arbeitsübersicht, die ich zu Anfang meiner Doktorarbeit einreichen musste, hatte ich einen kleinen Abschnitt eingefügt, der besagte, dass ich im Falle der Entdeckung eines Sterns mit [Fe/H] < –5 alle anderen Projekte in den Hintergrund stellen würde, um mich voll und ganz auf die Neuentdeckung zu konzentrieren. Und genau dieser aufregende Fall war eingetreten.

Wie angenommen zog diese sensationelle Entdeckung aber gleichzeitig sehr viel Arbeit nach sich. Denn nun musste schnellstmöglich eine detaillierte Analyse angefertigt und publiziert werden. Ein weiterer Stern mit [Fe/H] < –5.0 war ein äußerst wichtiger Fund, der zeigte, dass die Entdeckung von HE 0107-5240 keine Eintagsfliege gewesen war. Eine Gruppe von Sternen mit solchen winzigen Eisenmengen musste existieren, und unsere Suchmethoden bewiesen, dass wir sie finden konnten. Einen einzelnen Stern zu finden kann Zufall sein, zwei Sterne bedeuteten aber, dass wir dem frühen Universum und seinen Geheimnissen gut und sicher auf der Spur waren. Die Details der Häufigkeitsmuster dieser chemisch extrem seltenen Sterne sind deswegen schon in Kapitel 9.3 ausführlich beschrieben worden.

Im Spätsommer 2004 verbrachte ich daraufhin 6 Wochen in Japan, um gemeinsam mit dem deutschen und dem japanischen Kollegen an der Analyse und dem Manuskript zu arbeiten. Im April 2005 wurde die Entdeckung dann endlich von unserem internationalen neunzehnköpfigen Team unter meiner Leitung im Wissen-

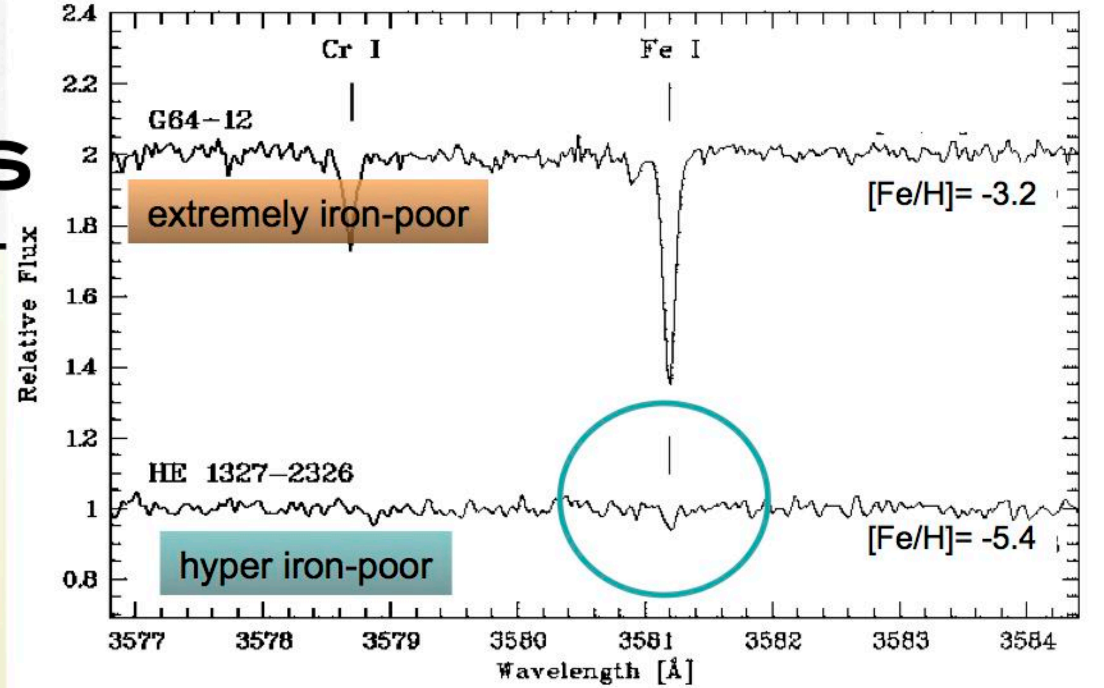
Tiny Little Iron Wiggles

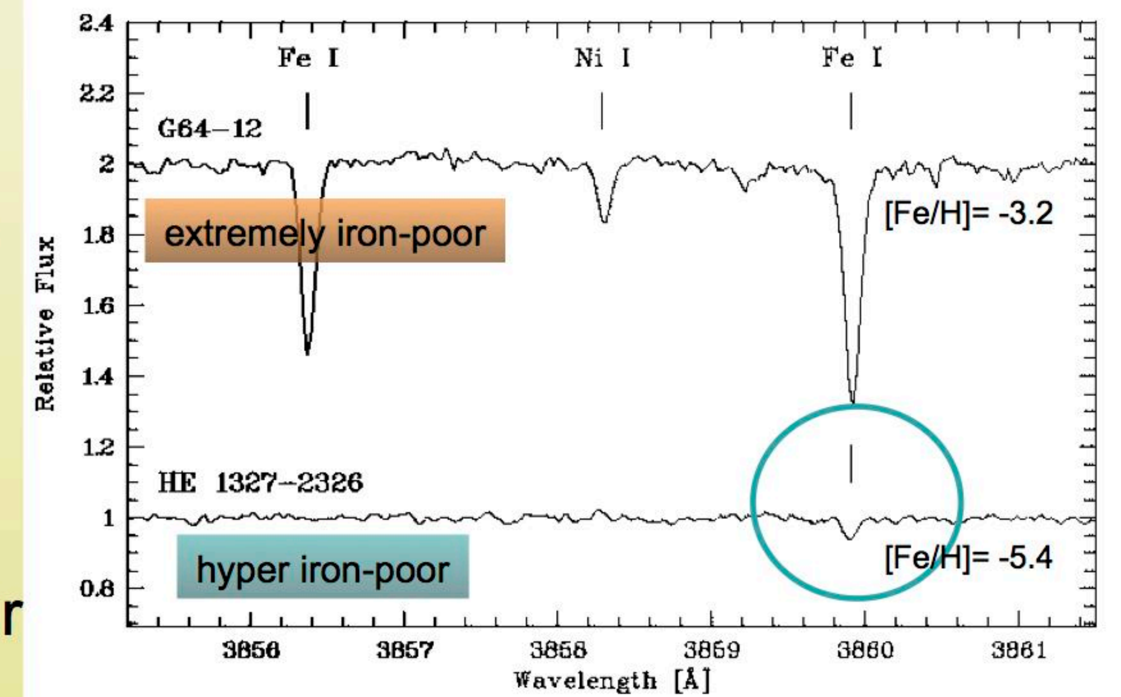
High-resolution (R~60,000) Subaru/HDS spectrum (7h exposure time; taken by Wako Aoki of NAOJ)

Record holder for the **lowest Fe abundance** observed in a star:

=> [Fe/H] = -5.4

⇒"Hyper iron-poor" star



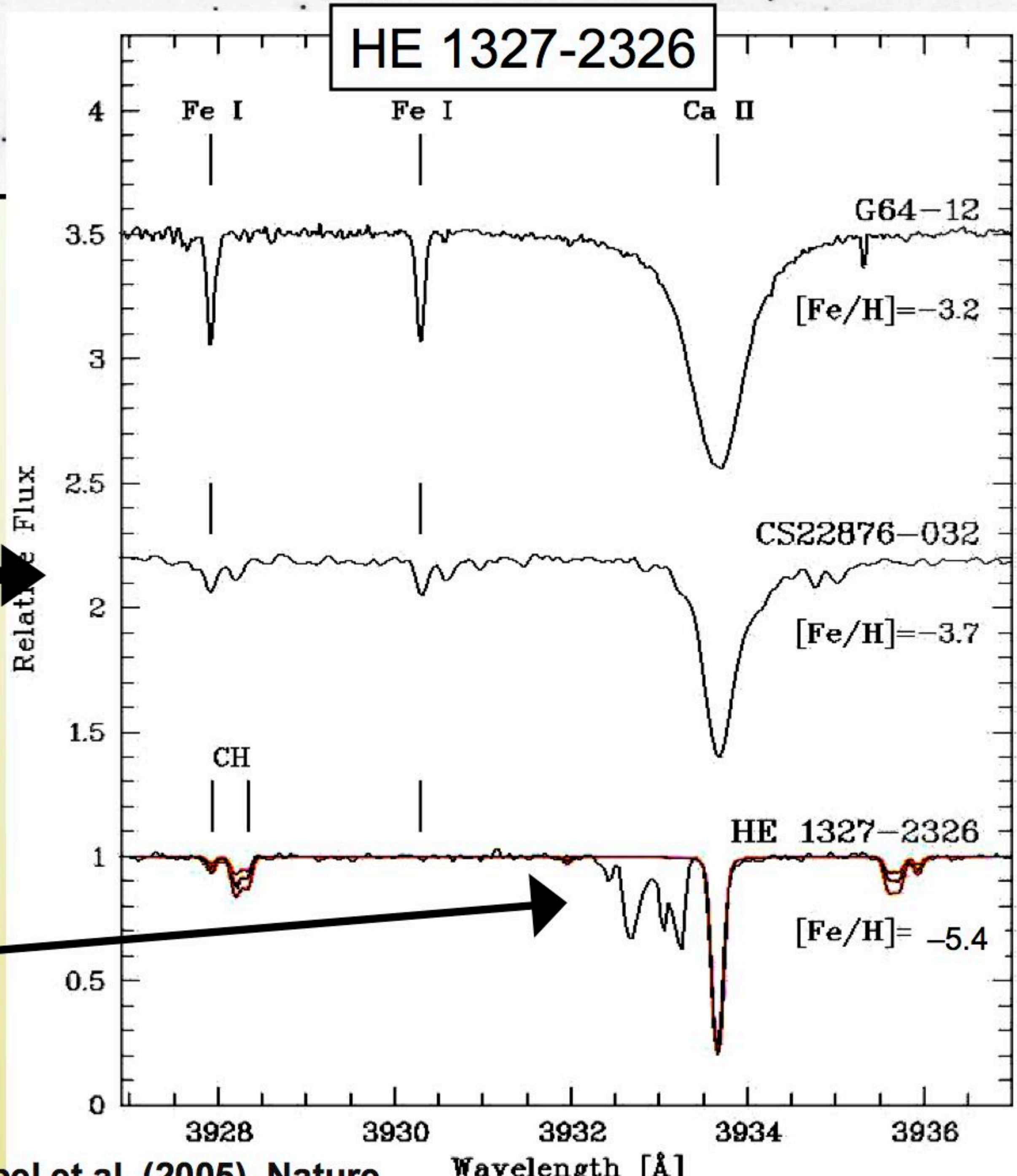


CA II K LINE

Calcium often used as proxy for the Fe abundance!
(..and Fe for metallicity)

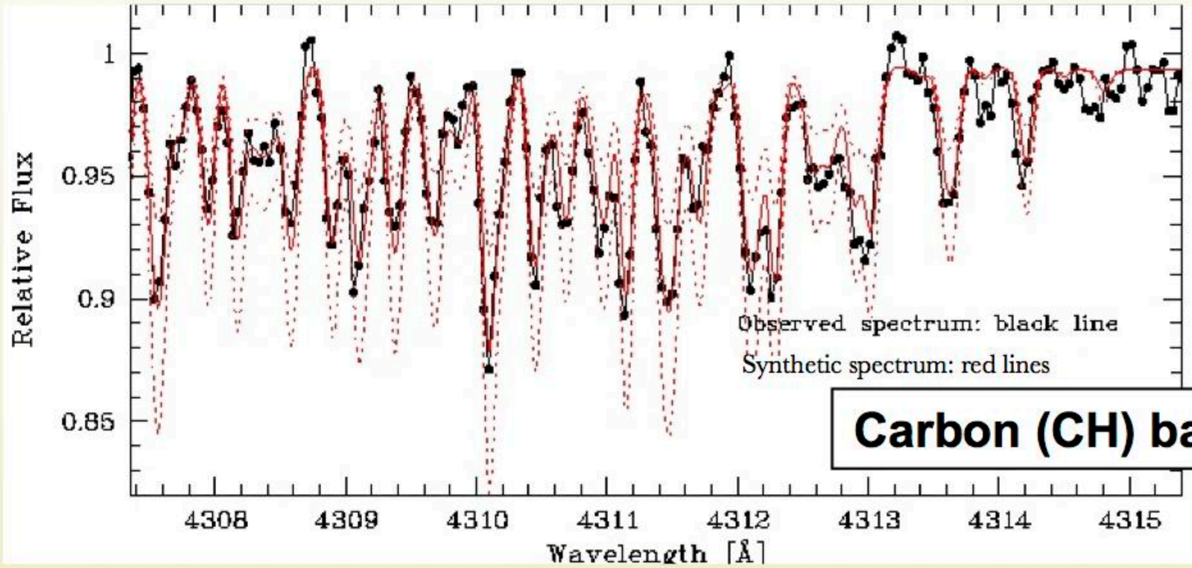
Double lined spectroscopic binary

Interstellar Ca
(Ca scales with Fe!)



Frebel et al. (2005), Nature

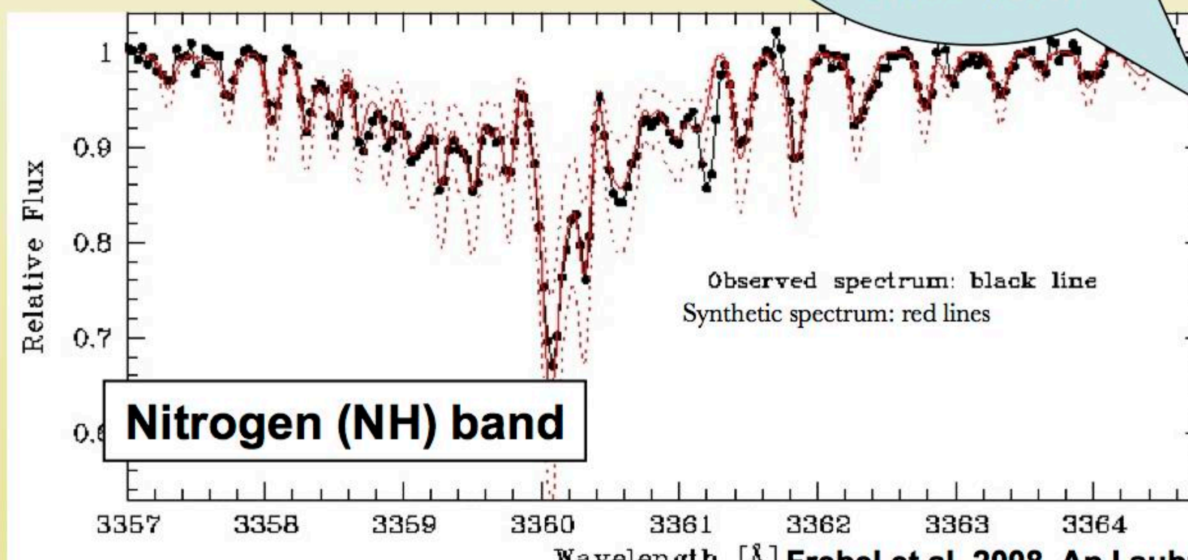
CARBON & NITROGEN



⇒ **Huge carbon abund. of [C/Fe]= +3.7:**
⇒ **Not so carbon-poor...**

5,000 and 12,000 times more carbon and nitrogen than iron!

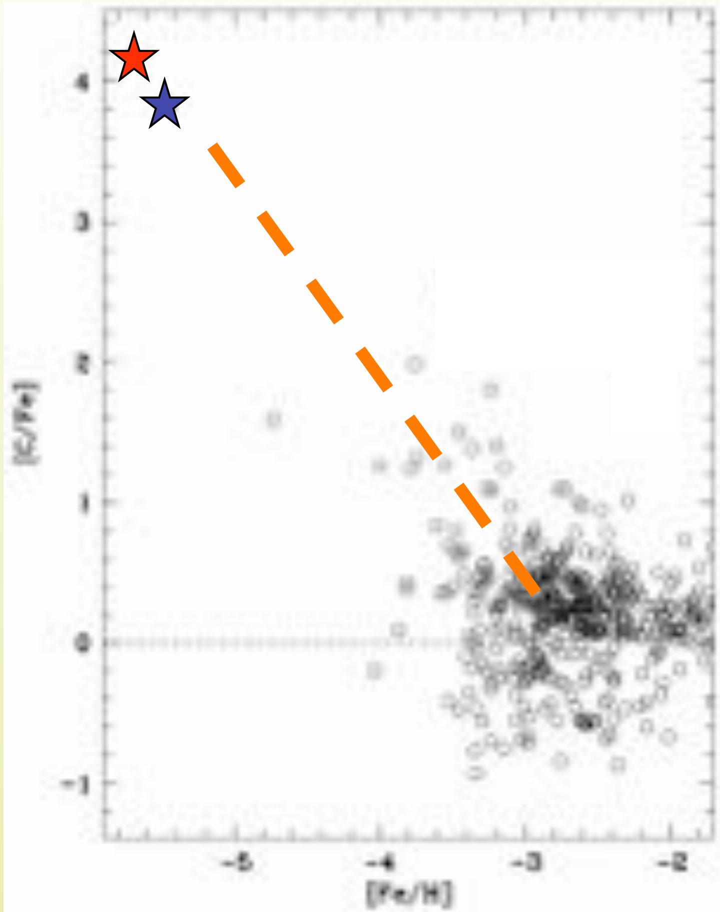
⇒ **Huge nitrogen abund. of [N/Fe]= +4.1:**
=> Not so nitrogen-poor...

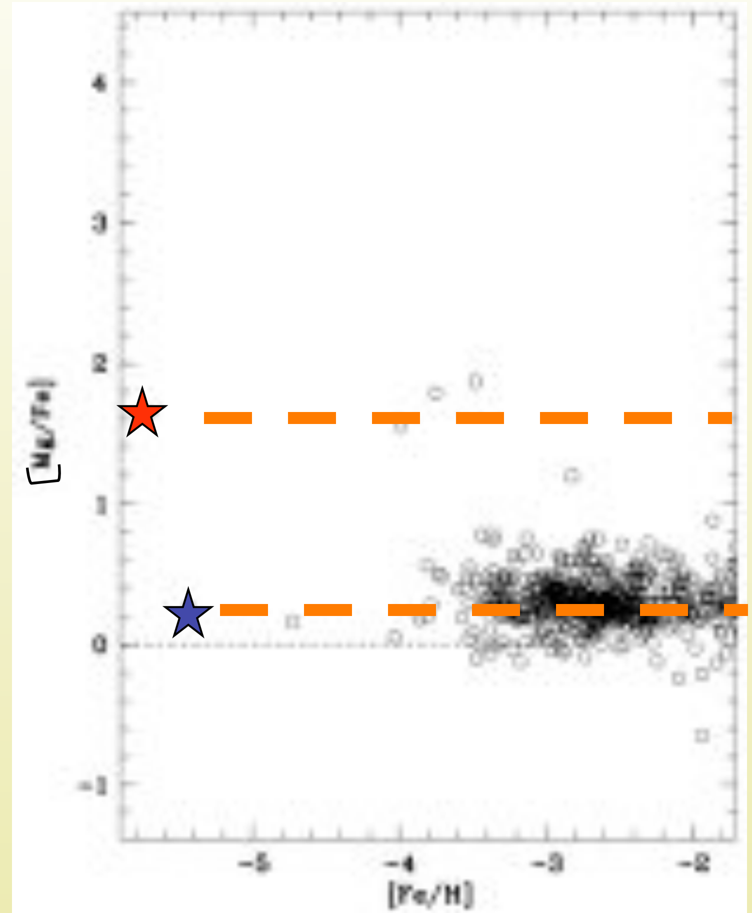


Frebel et al. 2008, ApJ subm.

Reminder:
Solar ratio [C,N/Fe] = 0

What is so special about the most Fe-poor stars?



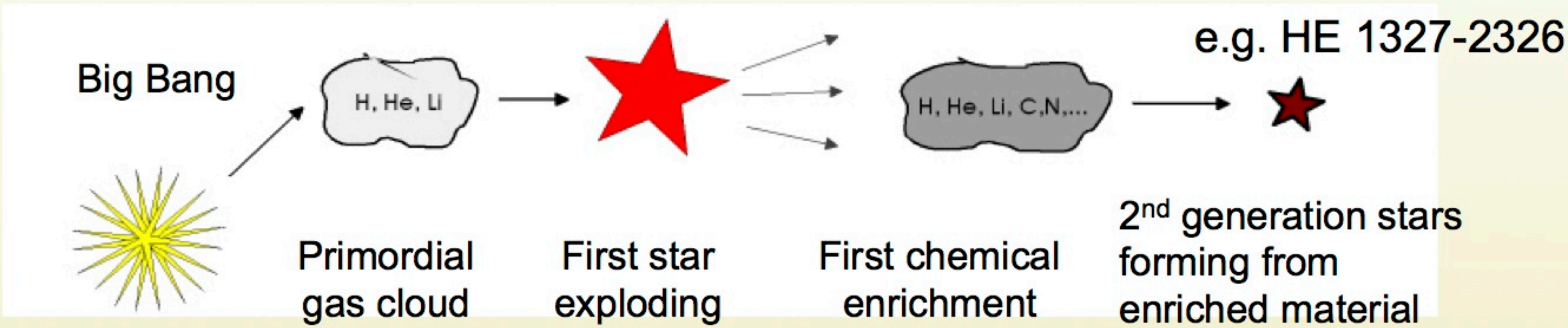


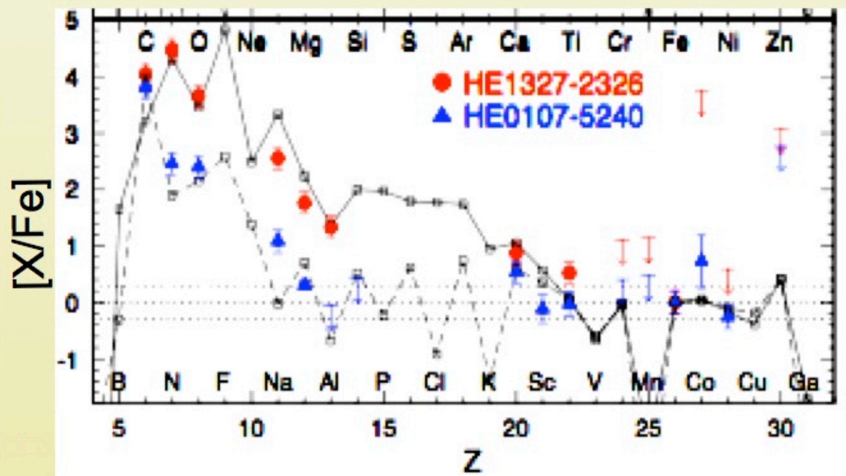
adapted from Aoki, Frebel et al. 2006, ApJ

The very different chemical signatures of the hyper iron-poor stars is crucial for understanding the formation of the elements!

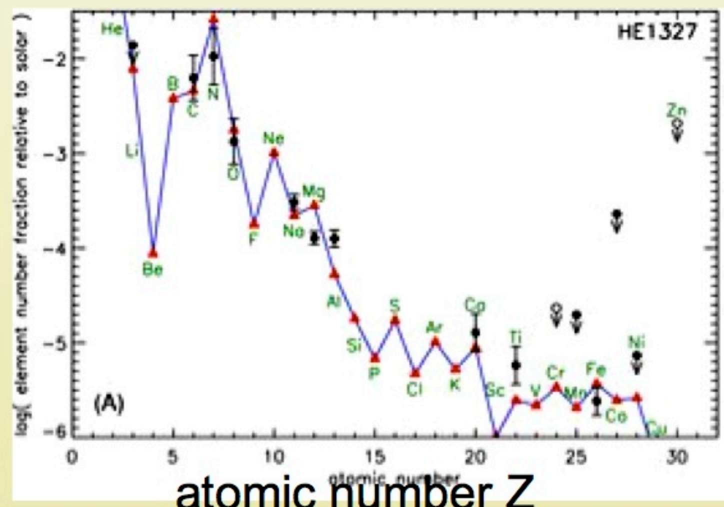
Review article on metal-poor stars plus all lit. data: Frebel 2010, Astr. Nachr.

How and when did these early stars form?





Tominaga et al. 2007



Heger & Woosley 2010

Why important?

Metal-poor stars provide the only available diagnosis for zero-metallicity Pop III nucleosynthesis and early chemical enrichment

QUICK SUMMARY:

The Milky Way halo contains stars with exceptionally low metallicities

HOW OLD ARE THE MOST METAL-POOR STARS?

ANNA FREBEL

METAL-POOR STARS

THE AGE OF THE OLDEST STARS

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, Californ
Mount Wilson and Palomar Observatories, C
California Institute of Technolog

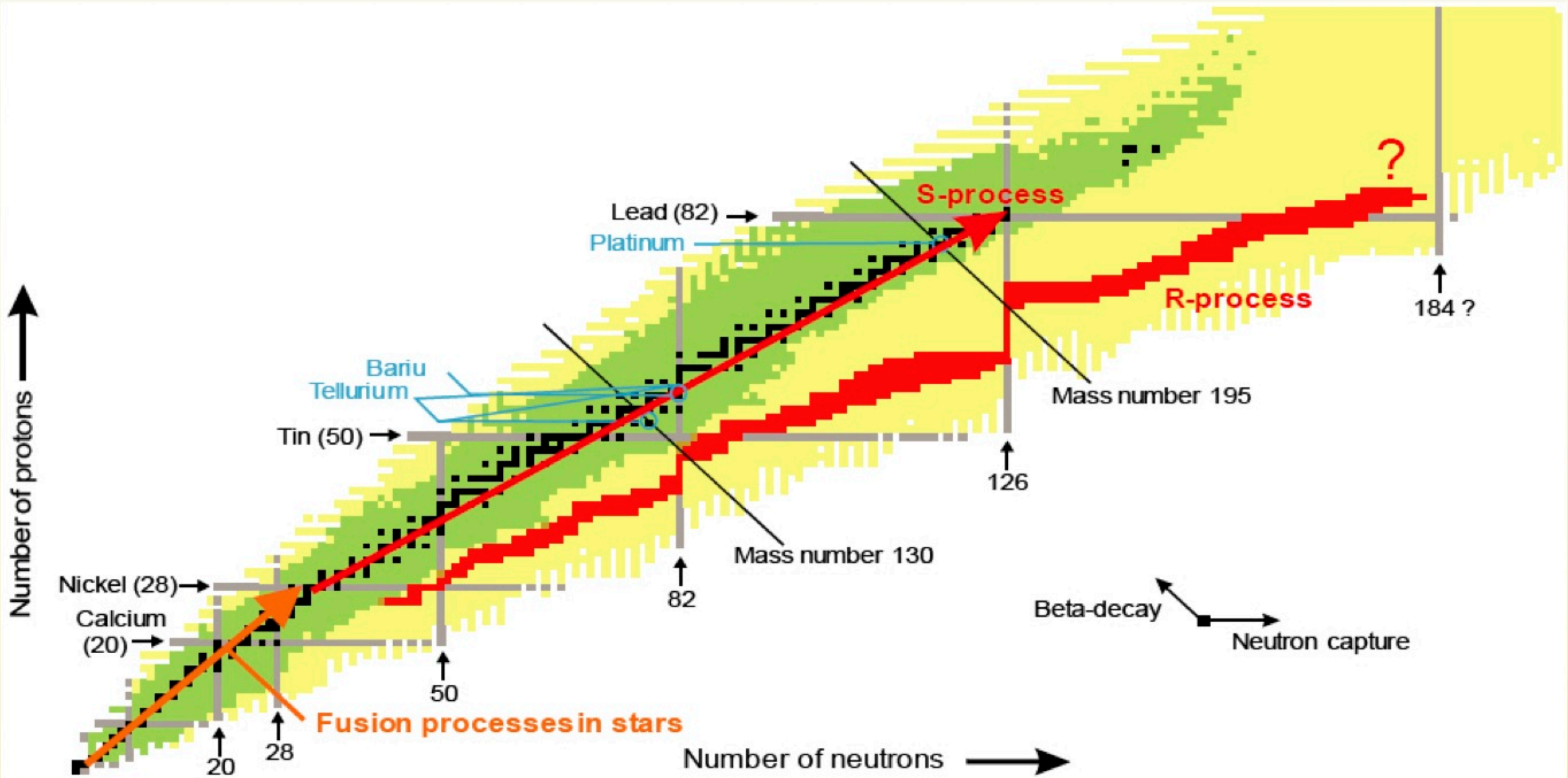
"B²FH"

E. r Process

The outstanding piece of observational evidence that this takes place is given by the explanation of the light curves of supernovae of Type I as being due to the decay of Cf^{254} (Bu56, Ba56), together with some other isotopes produced in the r process. Further evidence can be obtained only by interpreting the spectra of Type I supernovae, a problem which has so far remained unsolved.

***... there are old stars with this r-process signatures*!**

About the r-Process
(rapid neutron-capture process)



- s-process: neutron-capture longer than beta-decay timescale
- r-process: neutron-capture shorter than beta-decay timescale

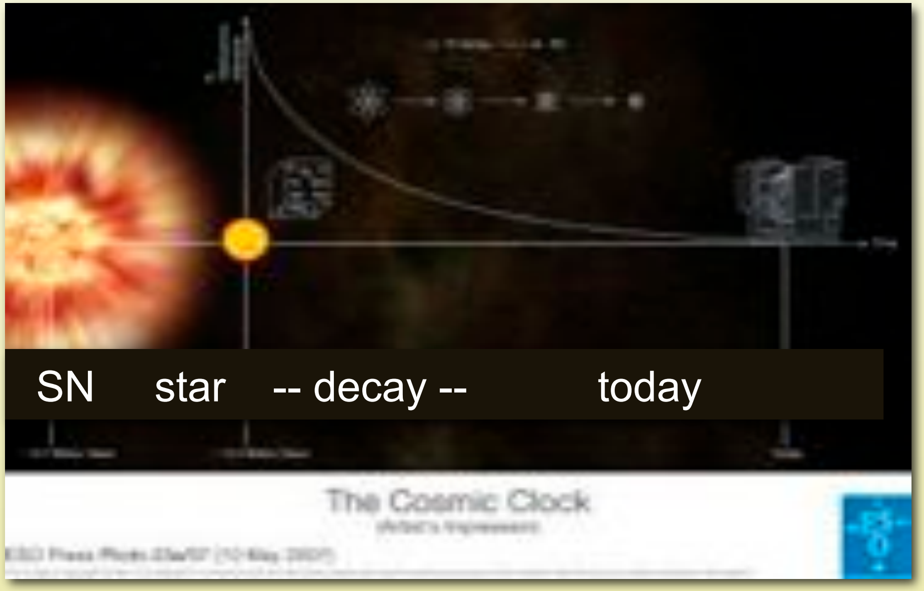
r-Process Enhanced Stars

(rapid neutron-capture process)

- Responsible for the production of the **heaviest elements**
- Most likely production site: **SNe II** => pre-enrichment
- **Chemical “fingerprint”** of previous nucleosynthesis event
  (only “visible” in the oldest stars bec. of low metallicity and one progenitor)

- ~**5%** of metal-poor stars with [Fe/H] < -2.5 (Barklem et al. 05)
  => Only 15-20 stars!

- **Nucleo-chronometry**:
  Stellar ages from radioactive Thorium and Uranium



[Th and U can also be measured in the Sun, but the chemical evolution has progressed too far -- required are old, metal-poor stars from times when only very few SNe had exploded in the universe]

RAPID NUCLEOSYNTHESIS EVIDENCE: HE 1523-0901

So, how many elements can you "see" in HE 1523-0901?

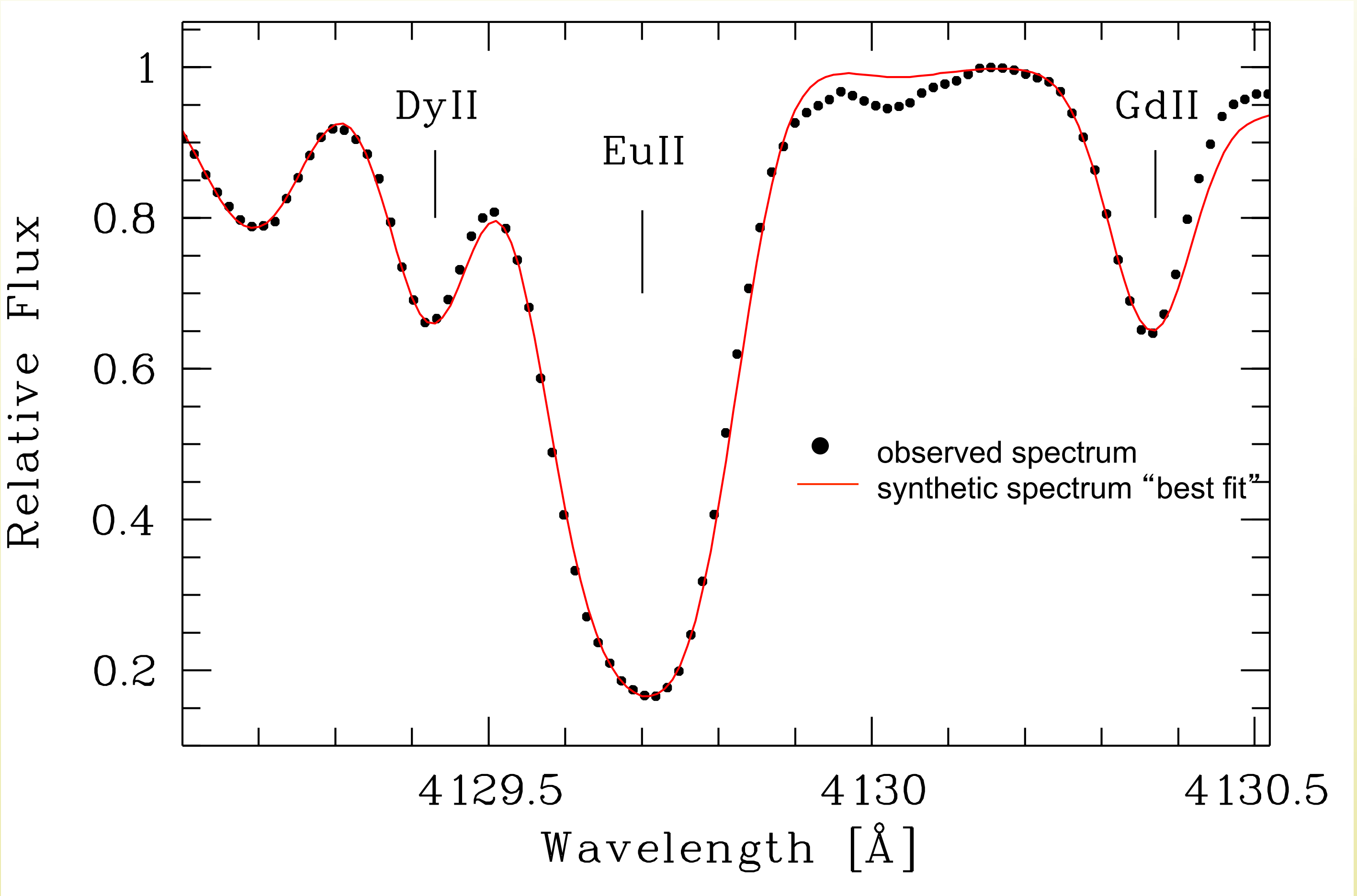
Magnitude: B = 12.1 mag
Metallicity: [Fe/H] = −3.0
"Extremely metal-poor star"

Frebel et al. 2007, ApJ 660, L117
Frebel et al. 2011, in prep.

ANNA FREBEL

METAL-POOR STARS

RAPID NUCLEOSYNTHESIS EVIDENCE: HE 1523-0901



Lanthanides or rare earth elements: i.e. Eu, Gd, Dy

Our Cosmic Lab

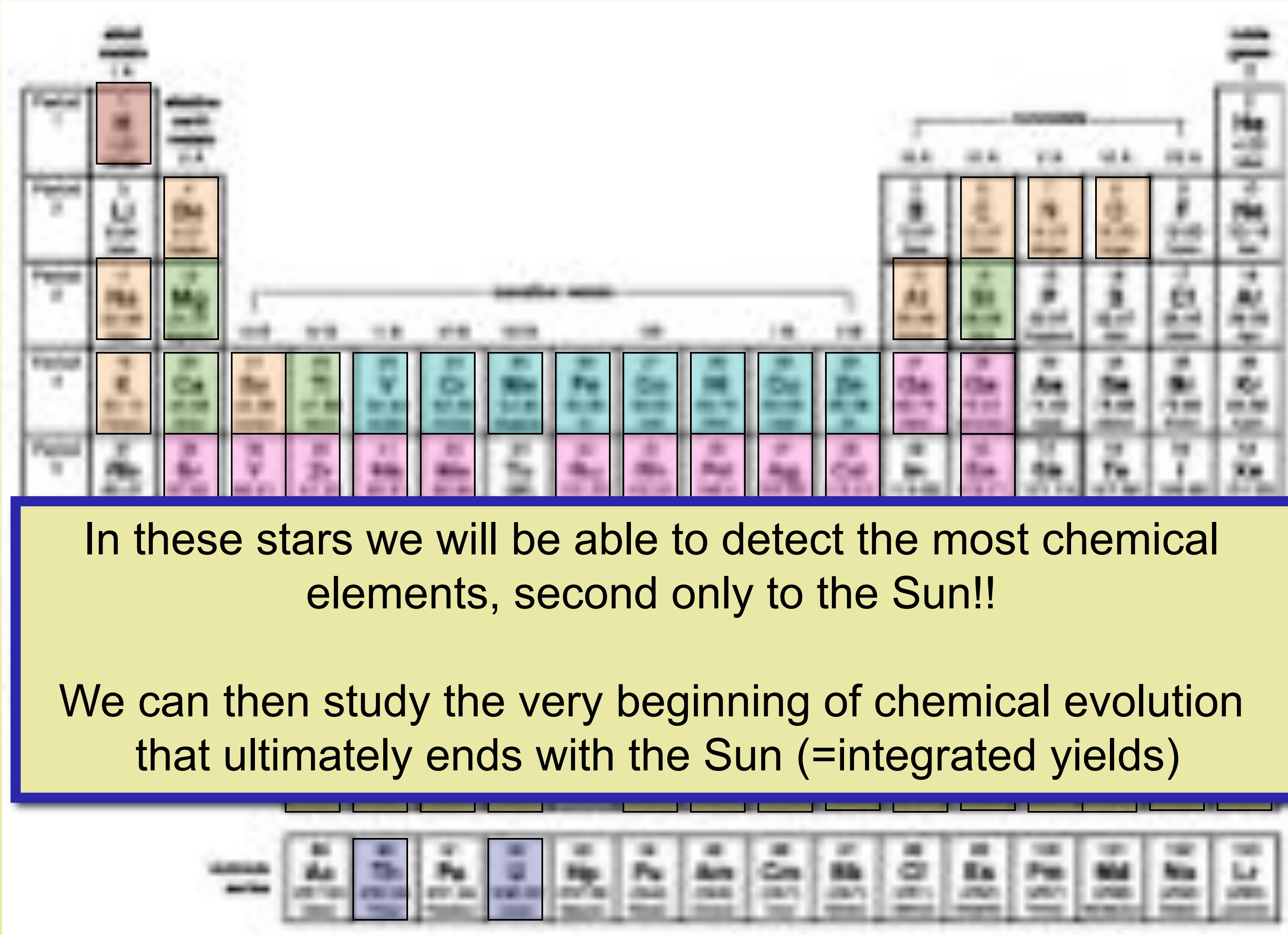
	alkali metals IA	alkaline earth metals IIA	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	noble gases O
Period 1	1 H 1.01 Hydrogen																	2 He 4.00 Helium
Period 2	3 Li 6.94 Lithium	4 Be 9.01 Beryllium											5 B 10.81 Boron	6 C 12.01 Carbon	7 N 14.01 Nitrogen	8 O 16.00 Oxygen	9 F 19.00 Fluorine	10 Ne 20.18 Neon
Period 3	11 Na 22.99 Sodium	12 Mg 24.31 Magnesium											13 Al 26.98 Aluminum	14 Si 28.09 Silicon	15 P 30.97 Phosphorus	16 S 32.07 Sulfur	17 Cl 35.45 Chlorine	18 Ar 39.95 Argon
Period 4	19 K 39.10 Potassium	20 Ca 40.08 Calcium	21 Sc 44.96 Scandium	22 Ti 47.88 Titanium	23 V 50.94 Vanadium	24 Cr 52.00 Chromium	25 Mn 54.95 Manganese	26 Fe 55.85 Iron	27 Co 58.93 Cobalt	28 Ni 58.70 Nickel	29 Cu 63.55 Copper	30 Zn 65.39 Zinc	31 Ga 69.72 Gallium	32 Ge 72.61 Germanium	33 As 74.92 Arsenic	34 Se 78.96 Selenium	35 Br 79.90 Bromine	36 Kr 83.80 Krypton
Period 5	37 Rb 85.47 Rubidium	38 Sr 87.62 Strontium	39 Y 88.91 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.91 Niobium	42 Mo 95.94 Molybdenum	43 Tc (98) Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.91 Rhodium	46 Pd 106.4 Palladium	47 Ag 107.87 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Indium	50 Sn 118.71 Tin	51 Sb 121.74 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.29 Xenon
Period 6	55 Cs 132.91 Cesium	56 Ba 137.33 Barium	Lanthanide series (see below)	72 Hf 178.49 Hafnium	73 Ta 180.94 Tantalum	74 W 183.85 Tungsten	75 Re 186.21 Rhenium	76 Os 190.23 Osmium	77 Ir 192.22 Iridium	78 Pt 195.08 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Tl 204.38 Thallium	82 Pb 207.2 Lead	83 Bi 208.98 Bismuth	84 Po (209) Polonium	85 At (210) Astatine	86 Rn (222) Radon
Period 7	87 Fr (223) Francium	88 Ra 226.03 Radium	Actinide series (see below)	104 Rf (261) Rutherfordium	105 Db (262) Dubnium	106 Sg (263) Seaborgium	107 Bh (262) Bohrium	108 Hs (265) Hassium	109 Mt (266) Meitnerium	110 (269)	111 (272)	112 (277)		114 (281)		116 (289)		118 (293)

nonmetals

transition metals

rare earth elements—Lanthanide series	57 La 138.91 Lanthanum	58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm (145) Promethium	62 Sm 150.4 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.93 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.93 Holmium	68 Er 167.26 Erbium	69 Tm 168.93 Thulium	70 Yb 173.04 Ytterbium	71 Lu 174.97 Lutetium
Actinide series	89 Ac 227.03 Actinium	90 Th 232.04 Thorium	91 Pa 231.04 Protactinium	92 U 238.03 Uranium	93 Np 237.05 Neptunium	94 Pu (244) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (247) Berkelium	98 Cf (251) Californium	99 Es (252) Einsteinium	100 Fm (257) Fermium	101 Md (258) Mendelevium	102 No (259) Nobelium	103 Lr (260) Lawrencium

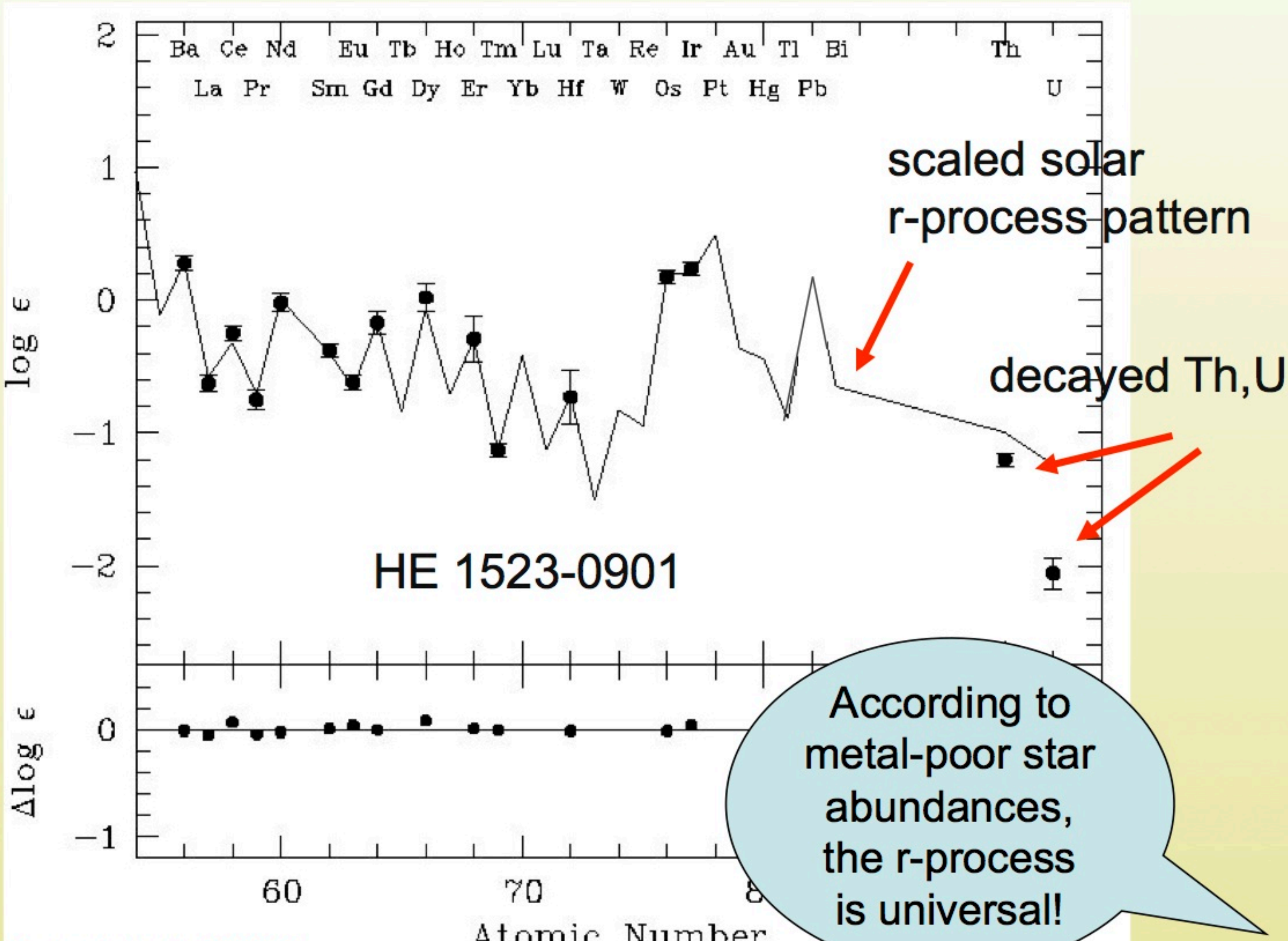
Our Cosmic Lab



In these stars we will be able to detect the most chemical elements, second only to the Sun!!

We can then study the very beginning of chemical evolution that ultimately ends with the Sun (=integrated yields)

THE r-PROCESS PATTERN

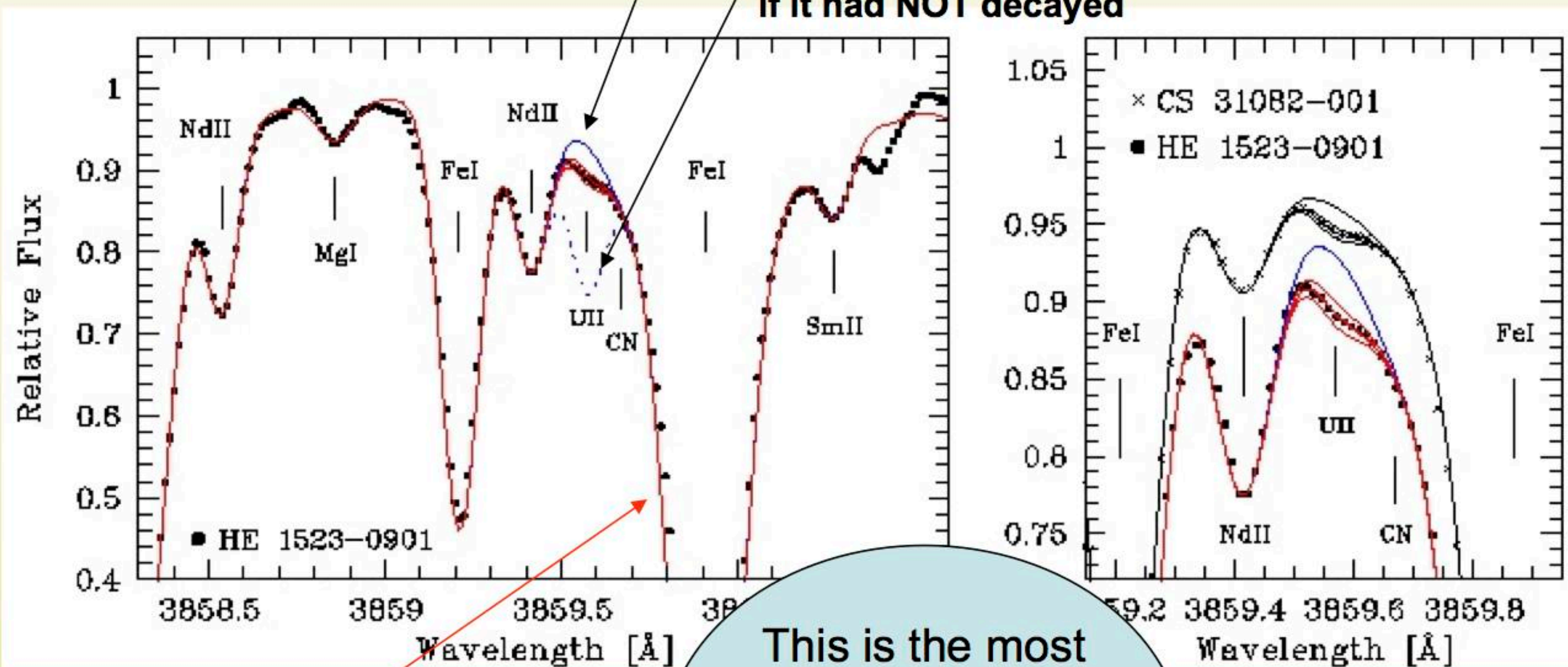


Frebel et al. (2007)

Uranium in HE 1523-0901

Synthetic spectrum that includes NO uranium

Synthetic spectrum with U abundance if it had NOT decayed



Frebel et al. (2007)

'Best fit' synthetic spectrum

This is the most reliable U detection! Only *two more* stars have measured U abundances.

THE AGE OF HE 1523-0901

Ages can be obtained from comparison of observed abundance ratio of a radioactive element (such as Thorium, Uranium) to a stable r-process element (such as Europium, Osmium, Iridium) and a theoretically derived initial production ratio.

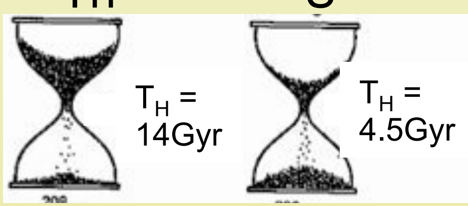
Done for Th/Eu for 20-30 stars (Sneden+96, Cayrel + 01, Johnson+Bolte 02, Christlieb+04)

$$\Delta t = 46.8 * (\log (Th/r)_0 - \log (Th/r)_{obs})$$

$$\Delta t = 14.8 * (\log (U/r)_0 - \log (U/r)_{obs})$$

$$\Delta t = 21.8 * (\log (U/Th)_0 - \log (U/Th)_{obs})$$

^{232}Th ^{238}U



^{208}Pb ^{206}Pb

Element ratio	Age [billion yrs]
Th/Eu	11.5
Th/Os	10.7
Th/Ir	15.0
U/Eu	13.2
U/Os	12.9
U/Ir	14.1
U/Th	13.0
average age	**~13 billion years**

Frebel et al. (2007)

WMAP age of the Universe: 13.7 Gyr
(Spergel et al. 07)

The Age of HE 1523-0901

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U/Ir	14.1
U/Th	13.0

Frebel et al. (2007)

For the first time more than one chronometer was be employed for a stellar age measurement!

⇒ (WMAP model-) Independent lower limit for age of the Universe

⇒ Other similarly metal-poor stars are probably similarly old

QUICK SUMMARY:

The Milky Way halo contains stars with exceptionally low metallicities

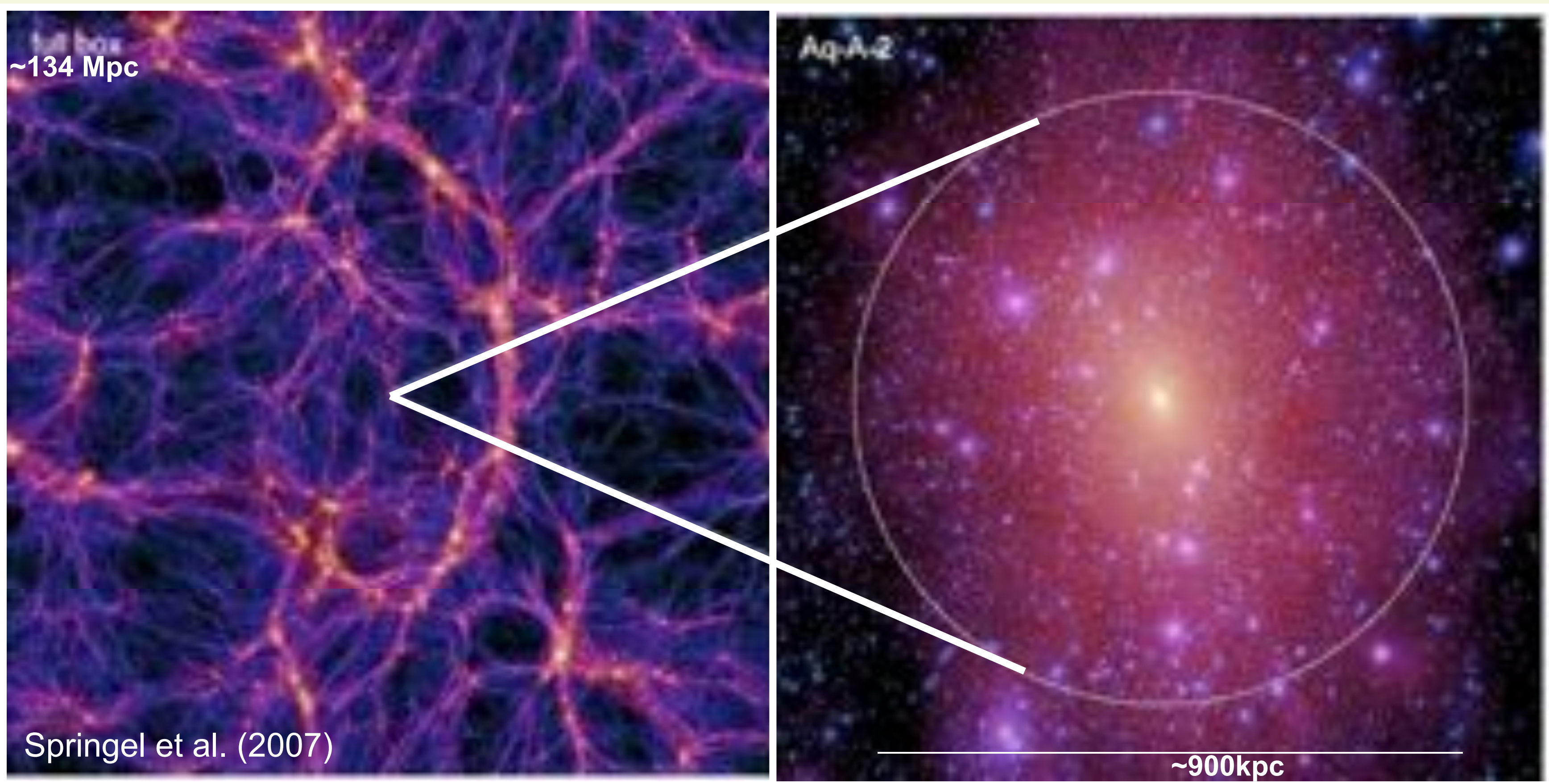
These stars are ~13 billion years old

WHERE DO THEY REALLY COME FROM?

The ΛCDM universe

CDM simulations of galaxy assembly show that **very few larger halos** plus **many smaller halos** merged to form the Galactic halo ("hierarchical growth").

Many small halos survive this process and are predicted to be around today.



Springel et al. (2007)

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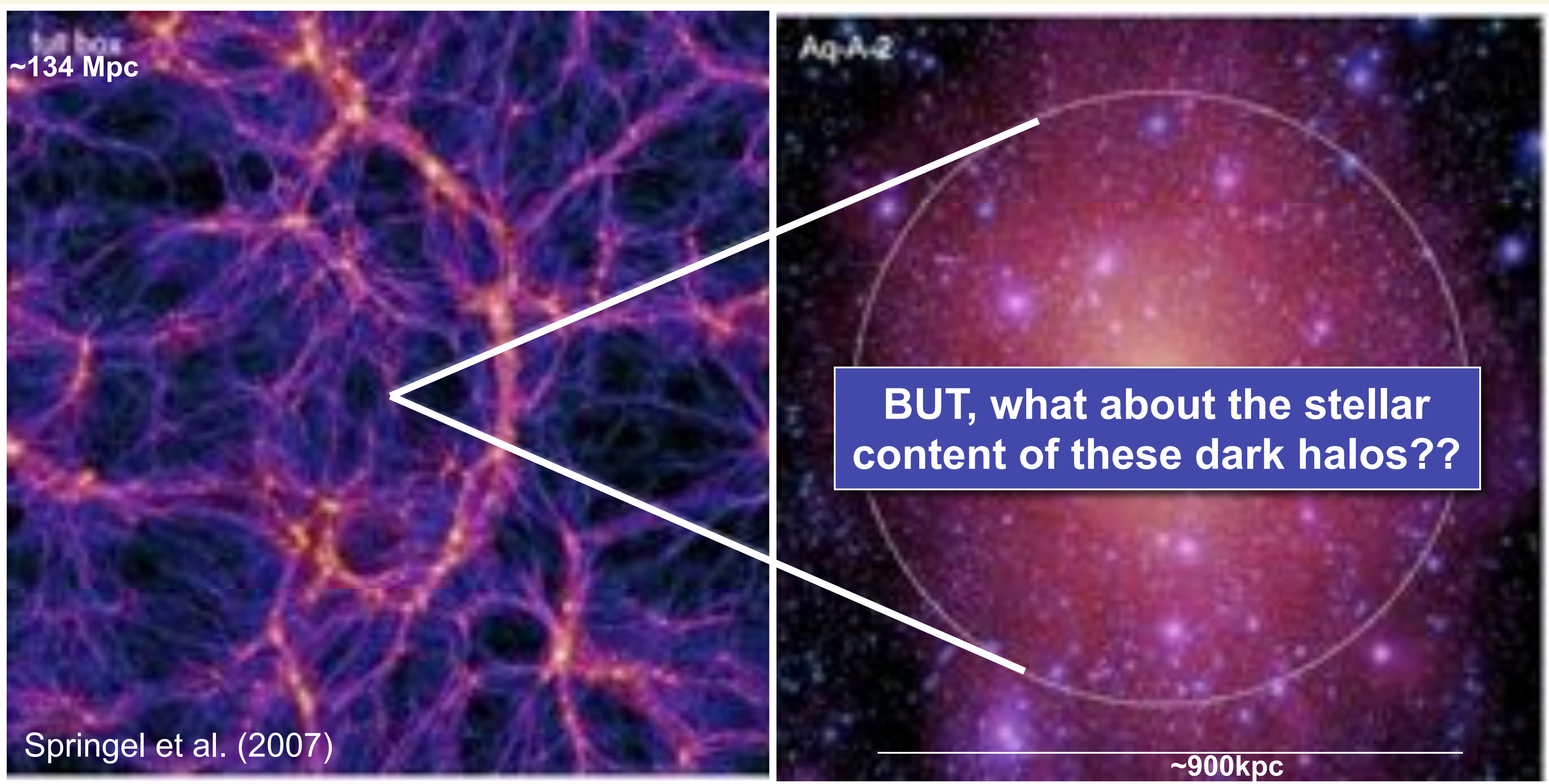
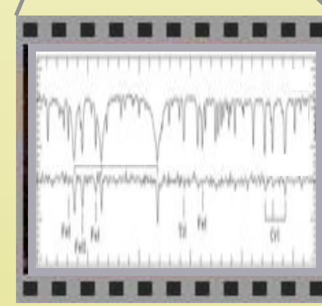


Using dwarf galaxies to study the nature of small halos

In the 'dark matter' world: λCDM hierarchical structure formation model

In the 'luminous' world: Comprehensive understanding of galaxy formation

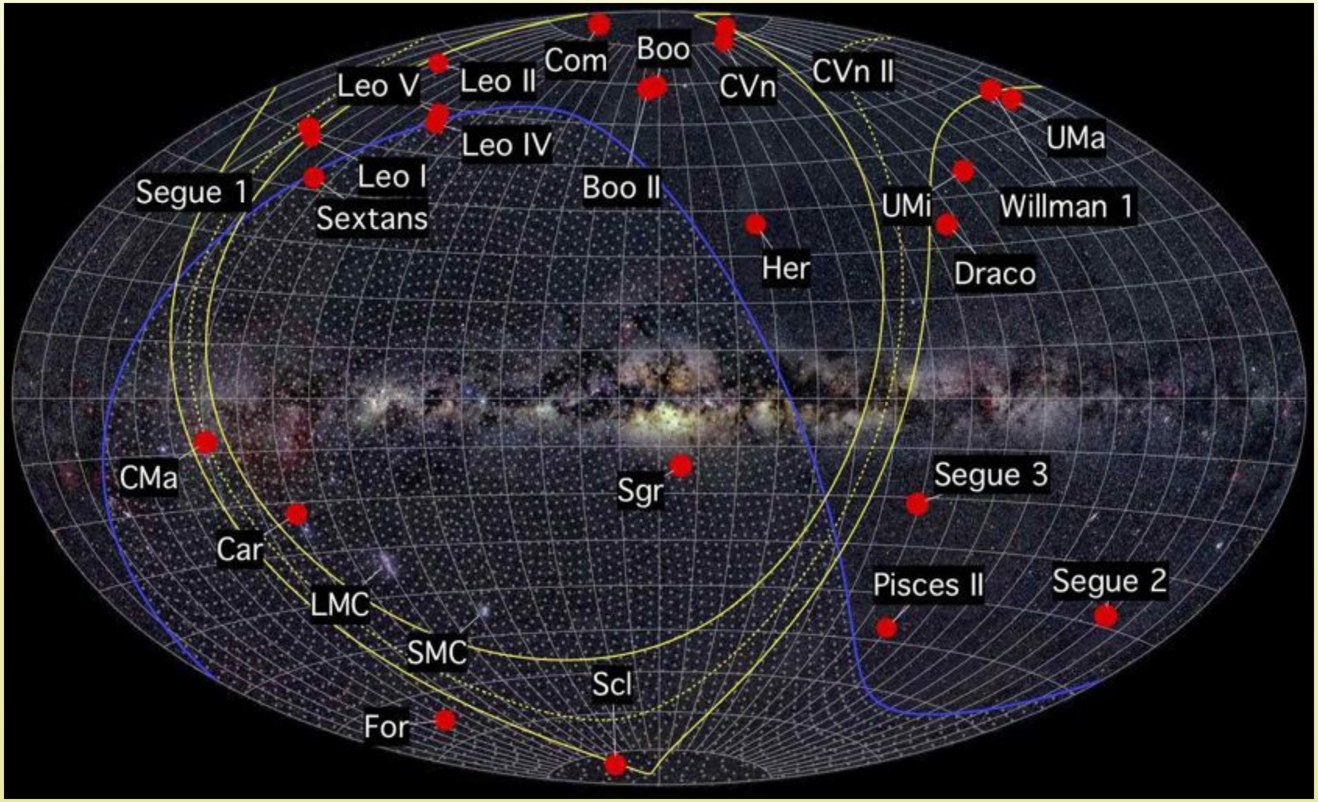
Spectroscopic observations of stars and streams (=luminous matter)



The Milky Way's satellites

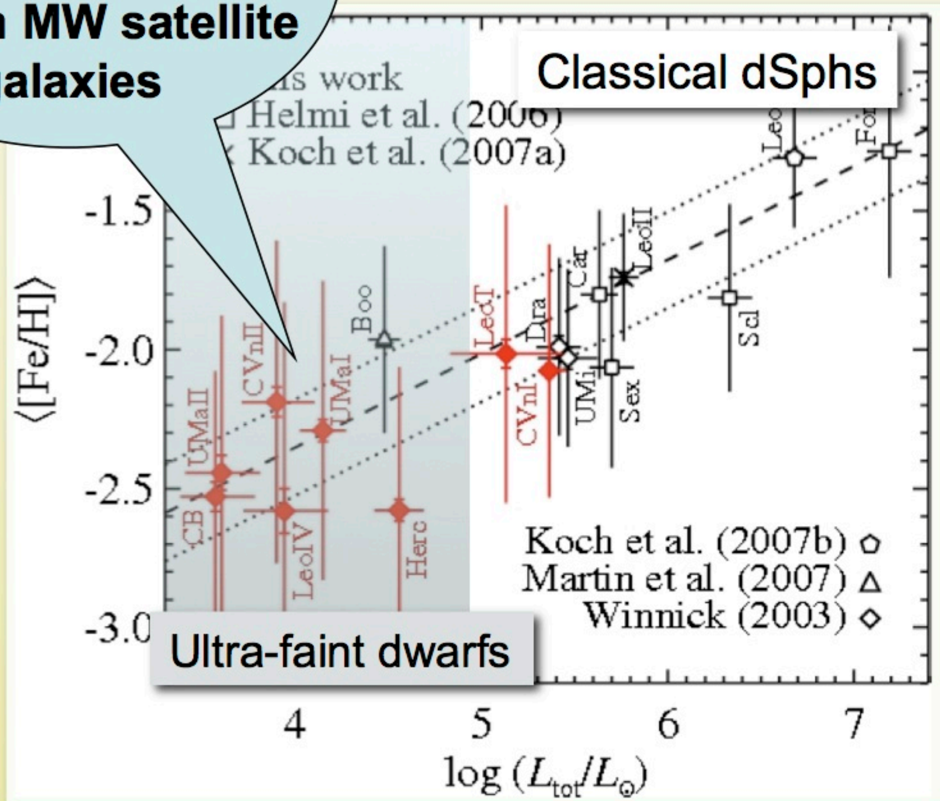
Dwarf galaxies are useful tools to study star formation and chemical evolution, early galaxy formation and the build-up of the Milky Way

dSph = gas poor dwarf galaxies dIrr = gas rich dwarf galaxies

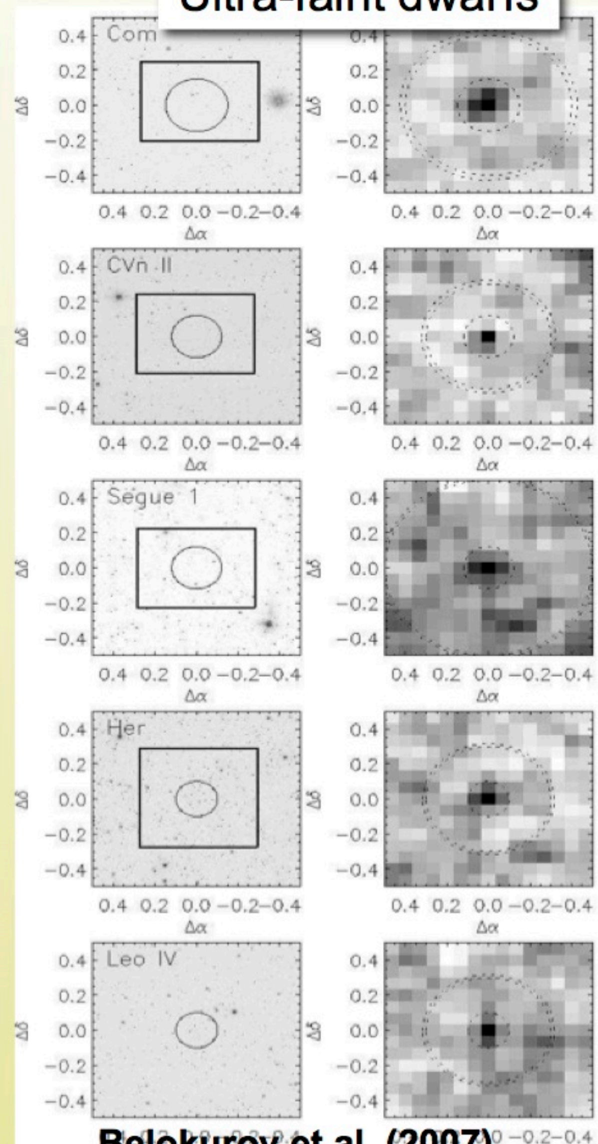


METALLICITY-LUMINOSITY RELATION

Stellar archaeology with the most metal-poor stars in MW satellite galaxies



Kirby et al. 2008



Belokurov et al. (2007)

Some interesting numbers...

- Total number of stars below [Fe/H] = -3.8 in Milky Way: **11** (2)
- Total number of stars below [Fe/H] = -3.8 in dwarfs: **4** (2)

- Total number of stars below [Fe/H] = -3.5 in Milky Way: **22** (2)
- Total number of stars below [Fe/H] = -3.5 in dwarfs: **8** (4)

Years to search for EMP stars:
Halo **~20 years**
Dwarfs **~3 years**

>30% of the most metal-poor stars known are in dwarfs!!

Segue 1 has 15% of all known stars below [Fe/H] = -3.5!
(it only has 7 stars bright enough for high-resolution spectr.)

CSI: Chemical Signatures, Investigated

Examine the chemical abundances of **individual dwarf galaxy stars**:

1) early chemical evolution *in small systems*

2) chemical signatures that can *relate dwarf galaxies to MW*

If surviving dwarfs are *analogs* of early MW building blocks then we should find chemical evidence of it!

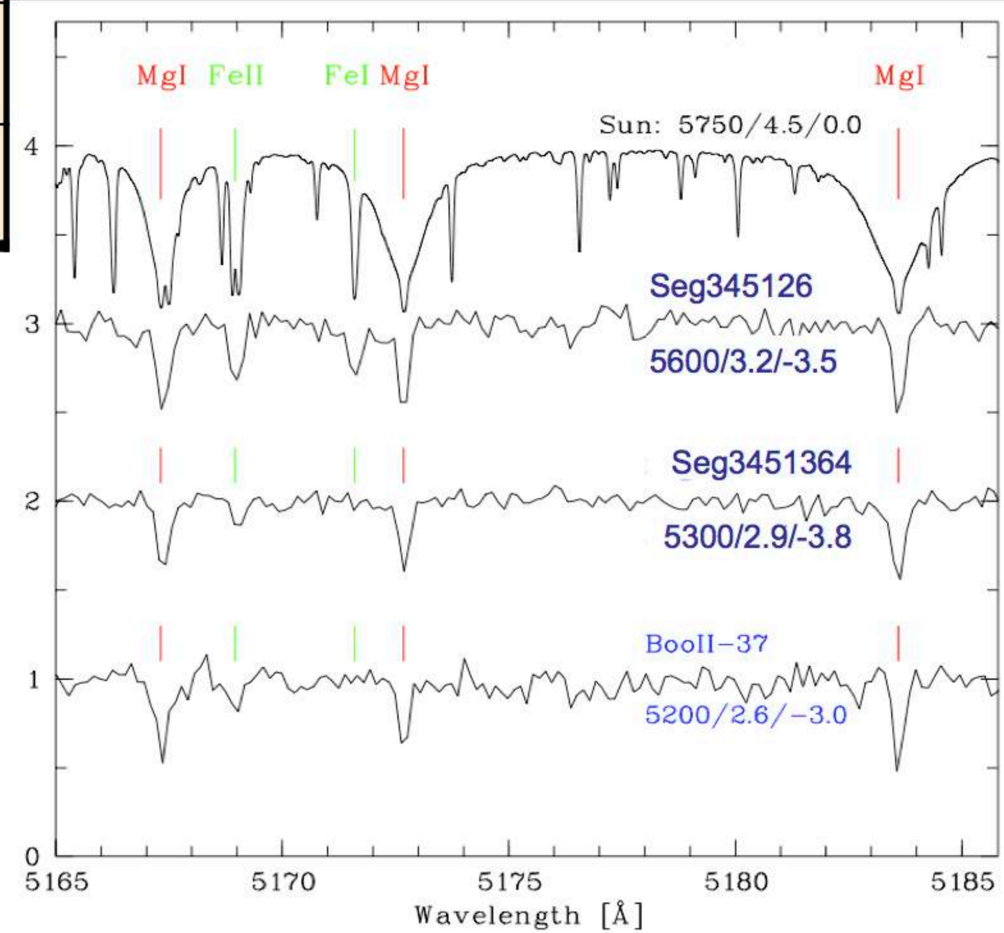
Stellar metallicities [Fe/H] & abundances [X/Fe] of metal-poor stars in dwarf galaxies **should agree** with those found in MW halo stars

And previous studies failed to find extremely metal-poor stars in the classical dwarfs; but their higher metallicity stars show different abundances...

Magellan/MIKE spectra

Star	g mag	t_{exp}	T_{eff} / log g / [Fe/H]
3451364 Segue 1	18.9	17 h	5300 / 2.9 / –3.8
3451326 Segue 1	19.4	7 h	5600 / 3.2 / –3.5
S37 Bootes II	19.5	14 h	5200 / 2.6 / –3.0

R~30,000



9h

17h

14h

Star 3451364, with [Fe/H]=–3.8, is the most metal-poor star in any of the ultra-faint dwarf galaxies!

Targets were selected from Kirby et al (*2008*) & Geha et al (*2009*)

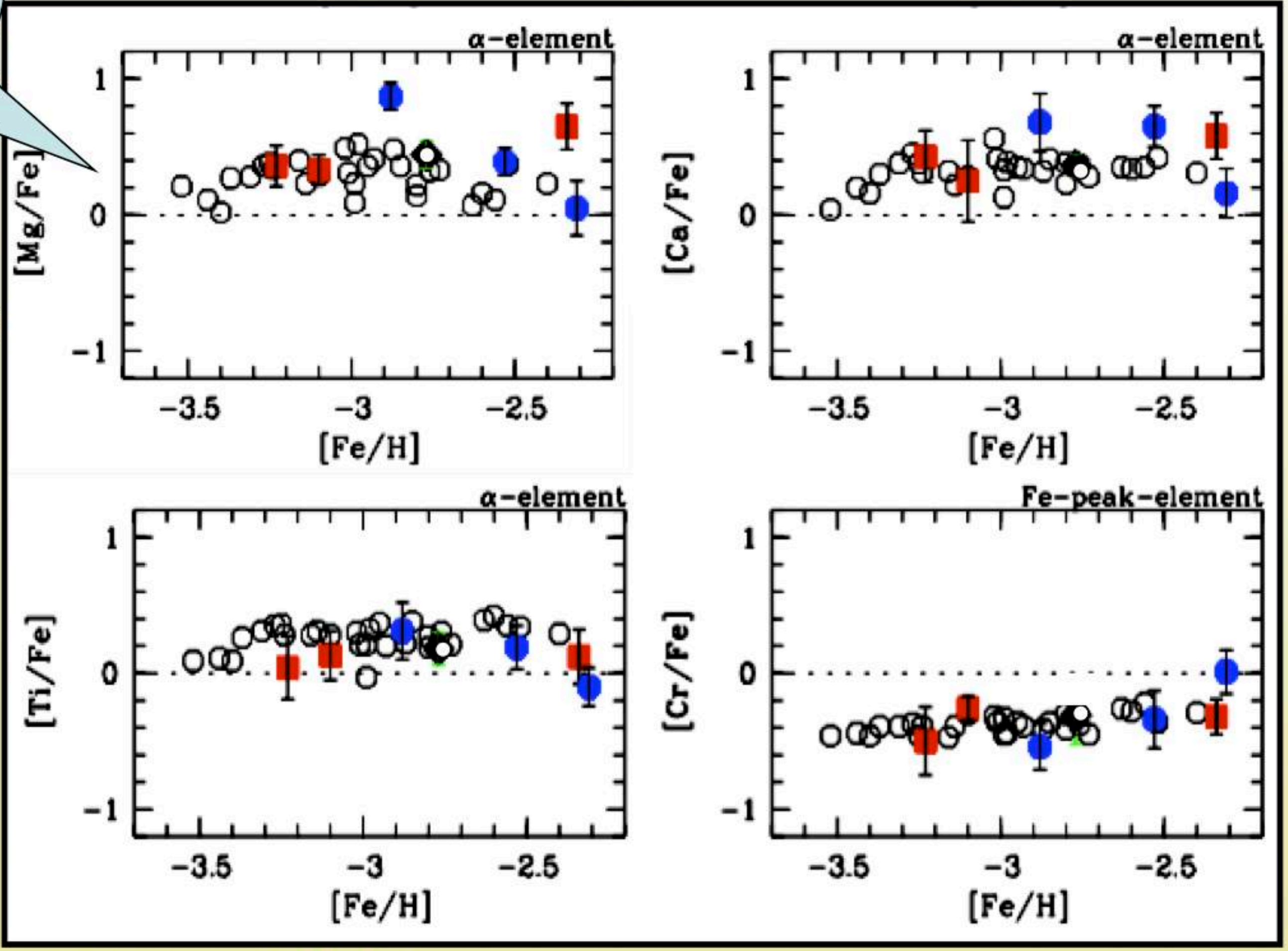
ULTRA-FAINT DWARF GALAXY STELLAR ABUNDANCE RATIOS

Excellent agreement with the MW chemical evolution

Black open circles: Halo stars

Red squares: Ursa Major II

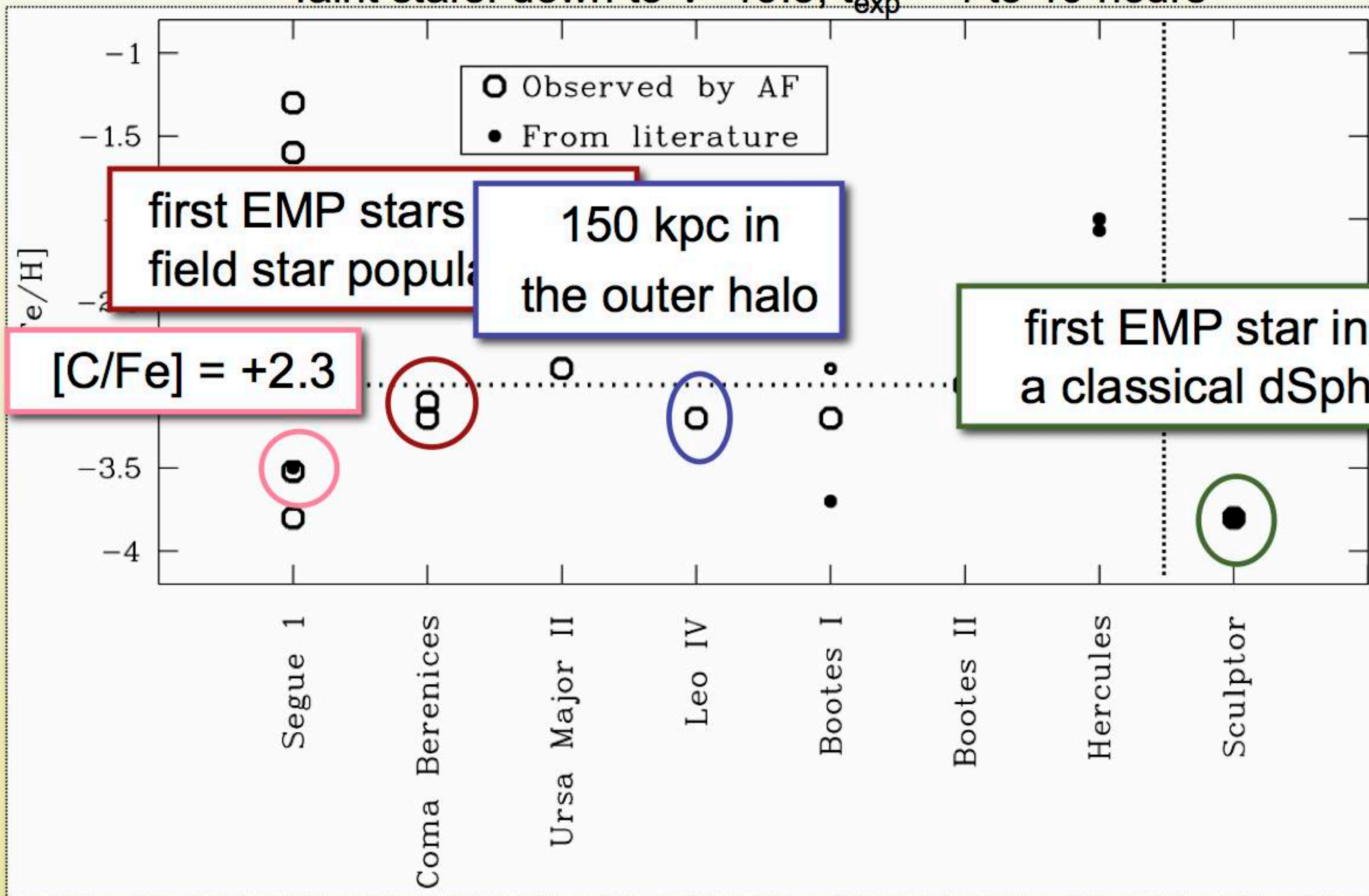
Blue dots: Coma Berenices



Frebel et al. (2010a)

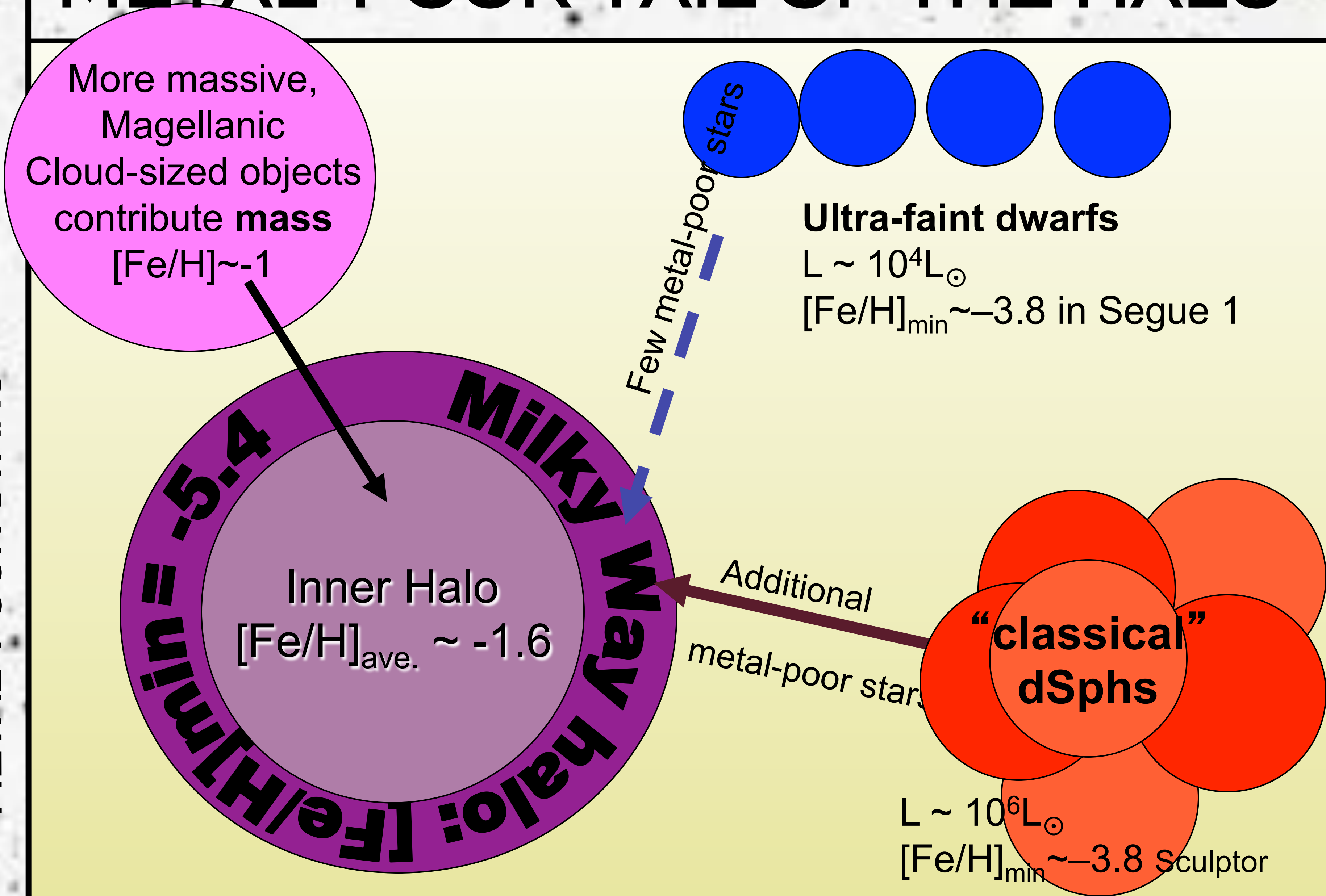
Status of high-resolution (R~30K) Spectroscopy of ultra-faint dwarf galaxy stars

faint stars: down to V=19.3, t_{exp} = 4 to 10 hours

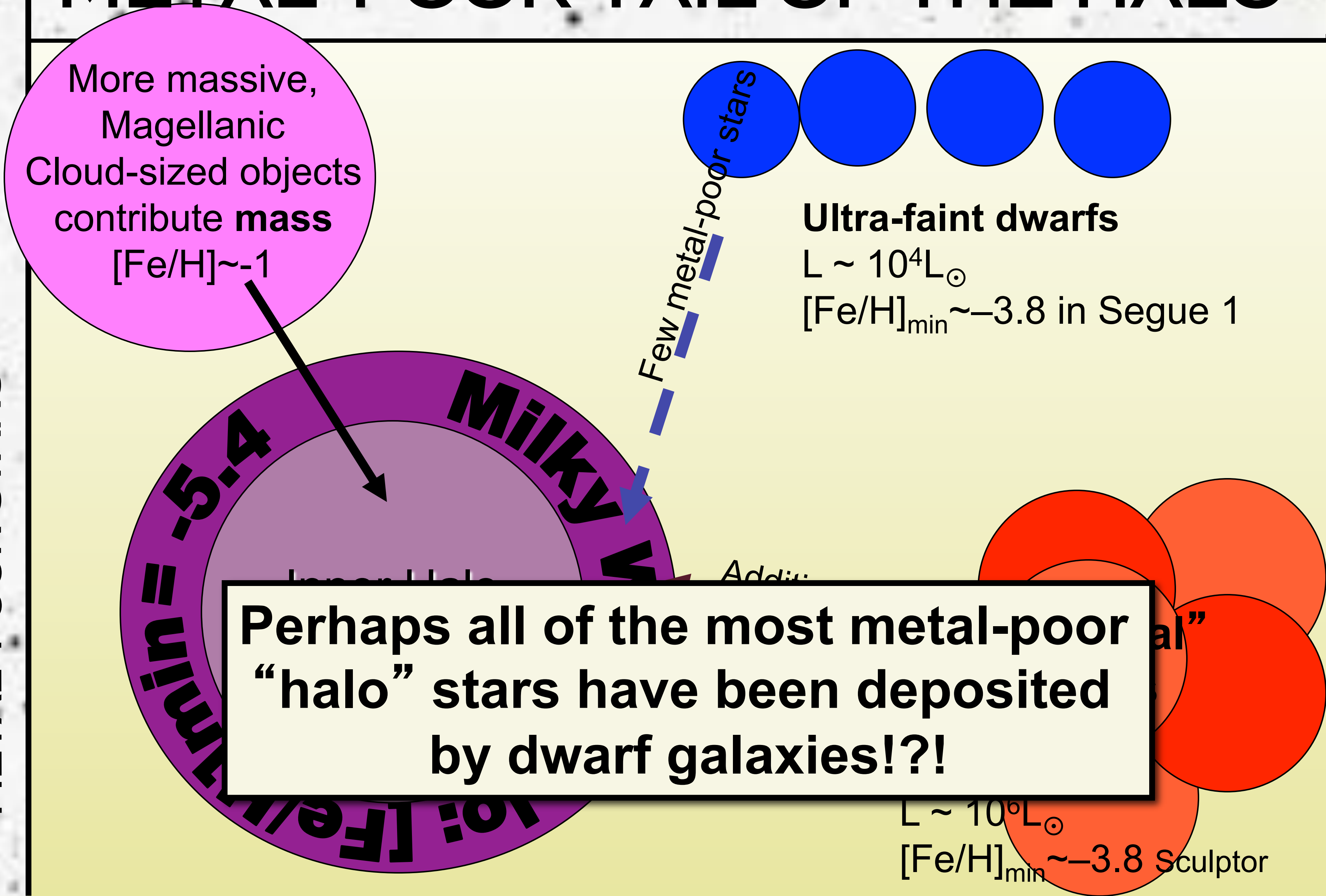


Frebel et al 2010
Simon, Frebel et al 2010
Frebel, Kirby & Simon 2010, Nature
Norris et al. 2010a+b
Frebel et al 2011a+b in prep.

ASSEMBLY OF THE METAL-POOR TAIL OF THE HALO



ASSEMBLY OF THE METAL-POOR TAIL OF THE HALO

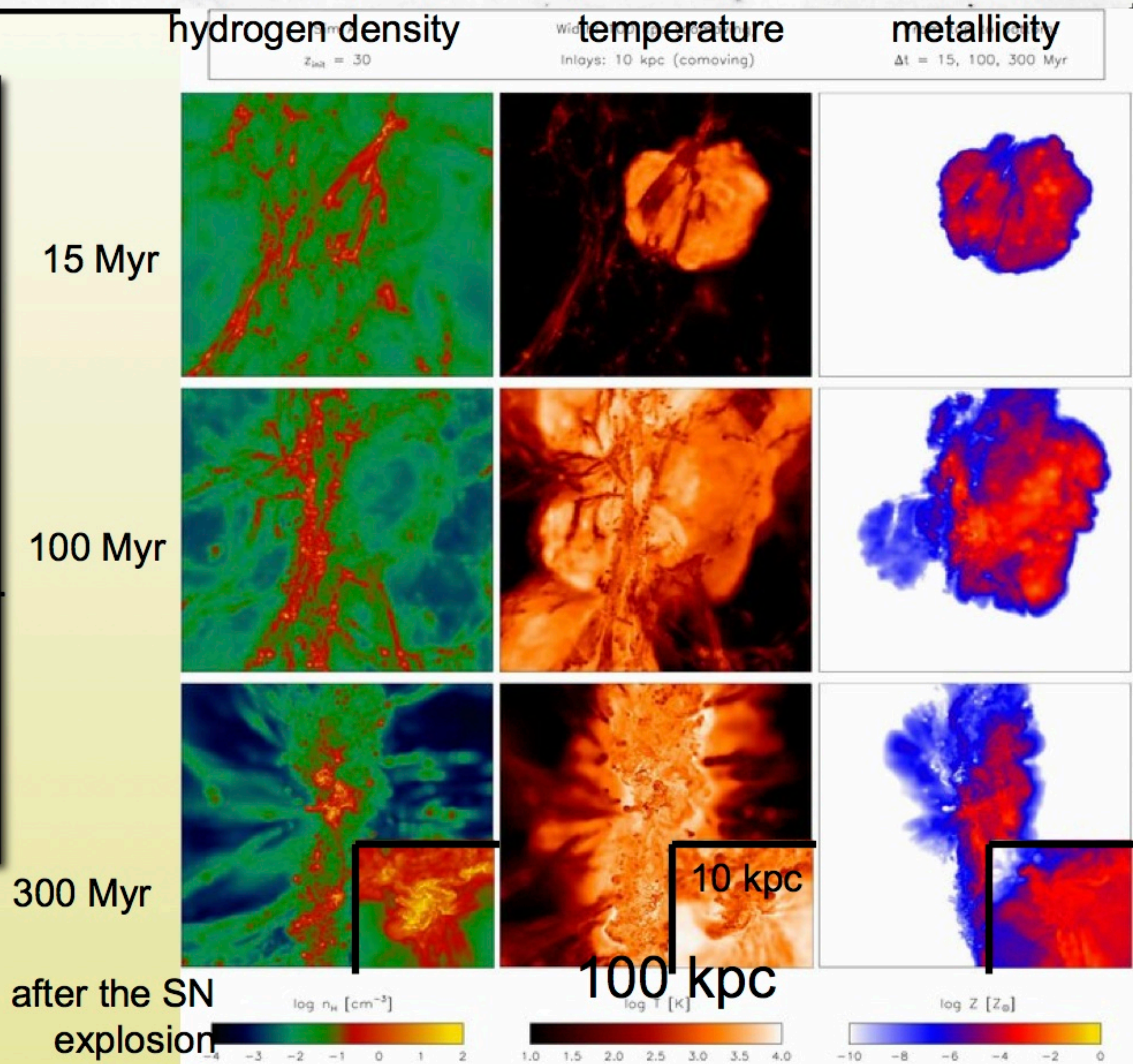


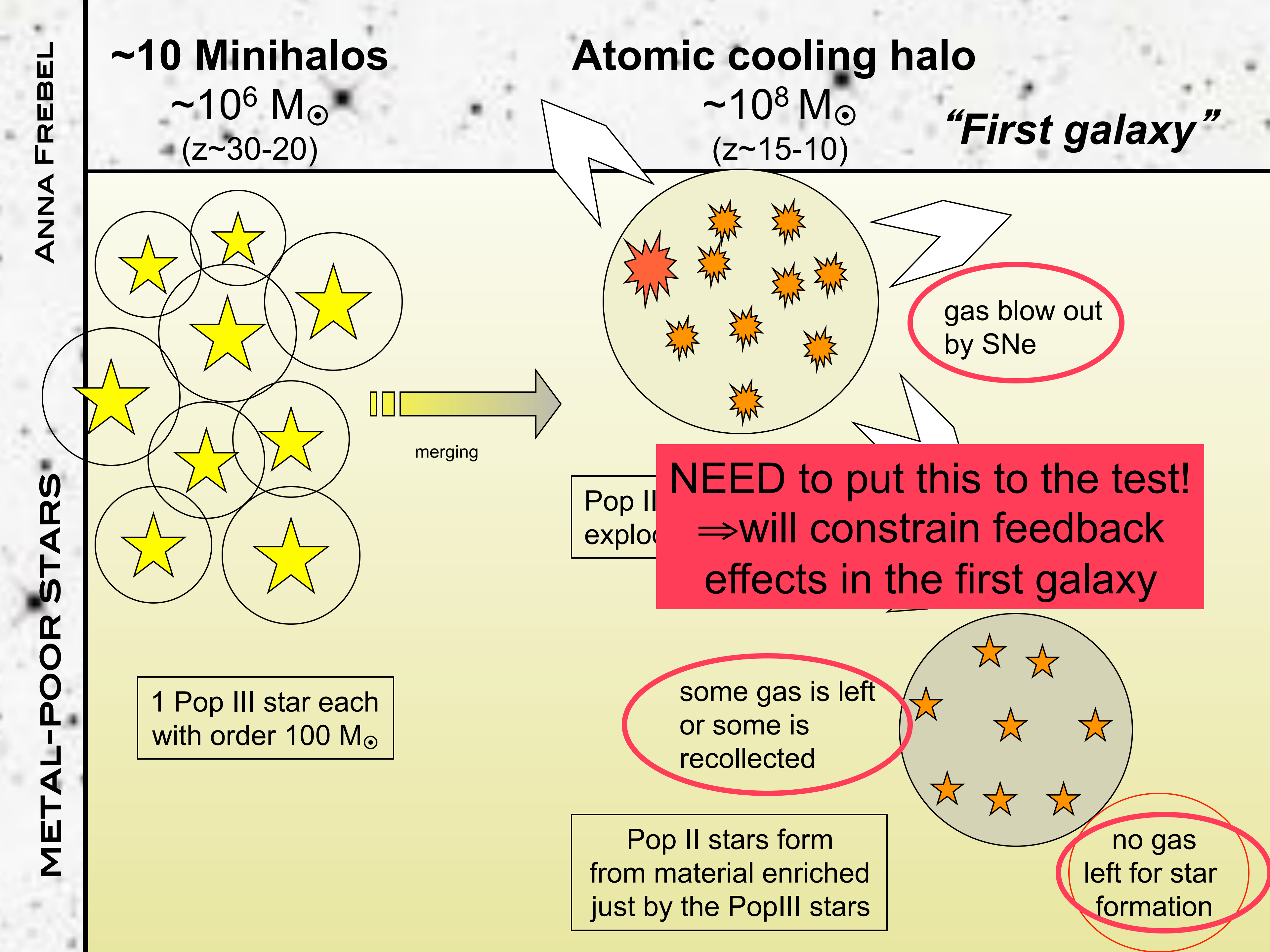
The chemical signature of the first galaxy

Motivation

Study the beginning of star and galaxy formation based on detailed ab-initio hydro simulations of the first stars and the assembly of the first galaxy

(e.g., Greif+10,11)




ANNA FREBEL
METAL-POOR STARS
~10 Minihalos
~10^6 M⊙
(z~30-20)
Atomic cooling halo
~10^8 M⊙
(z~15-10)
“First galaxy”
gas blow out by SNe
merging
NEED to put this to the test!
⇒will constrain feedback effects in the first galaxy
1 Pop III star each with order 100 M⊙
some gas is left or some is recollected
Pop II stars form from material enriched just by the PopIII stars
no gas left for star formation

ANNA FREBEL

ENRICHMENT CHANNELS IN A FIRST GALAXY

These enrichment events will not be sampled by later generations of stars in a such a first galaxy!

first galaxy enriched by Pop III stars; **one burst of SF**

low-mass stars survive until today => we observe those!

No additional star formation due to lack of gas!

formation of the first galaxy from ~10 mini halos

second-gen. metal-poor stars, w/ some MF

higher-mass stars: AGB stars some: SN II

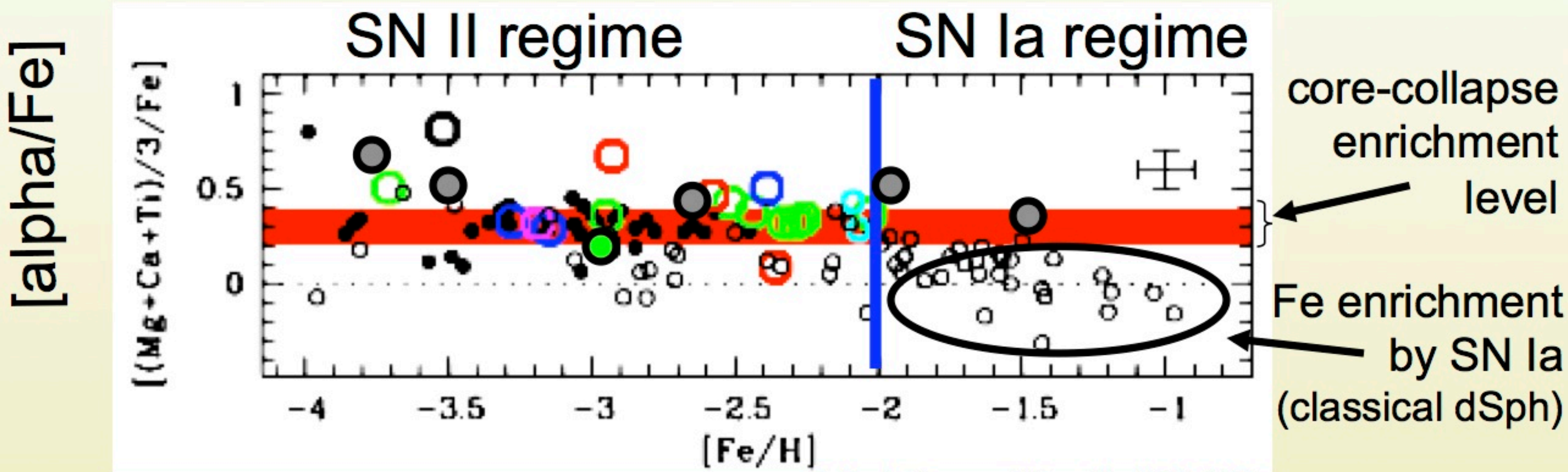
lower-mass stars: SN Ia

Time

today

METAL-POOR STARS

The abundance test!



Frebel + Bromm '11, arXiv/1010.1261
(data from Feltzing et al. 2009; Frebel et al. 2010b; Norris et al. 2010c; Simon et al. 2010; Norris et al. 2010a; Aden et al. 2011; Cayrel et al. 2004; Francois et al. 2007; Venn et al. 2004)

<u>Prediction:</u>
In a first galaxy no stars should show abundance patterns that reflect AGB or SN Ia enrichment!

AGB enrichment: can be tested with other elements

<u>First galaxy candidates:</u>
Ursa Major II, **Segue 1** & **Bootes I**, but also Coma Berenices, Leo IV
(Hercules not! $L \sim 6 \times 10^4 L_{sun}$)

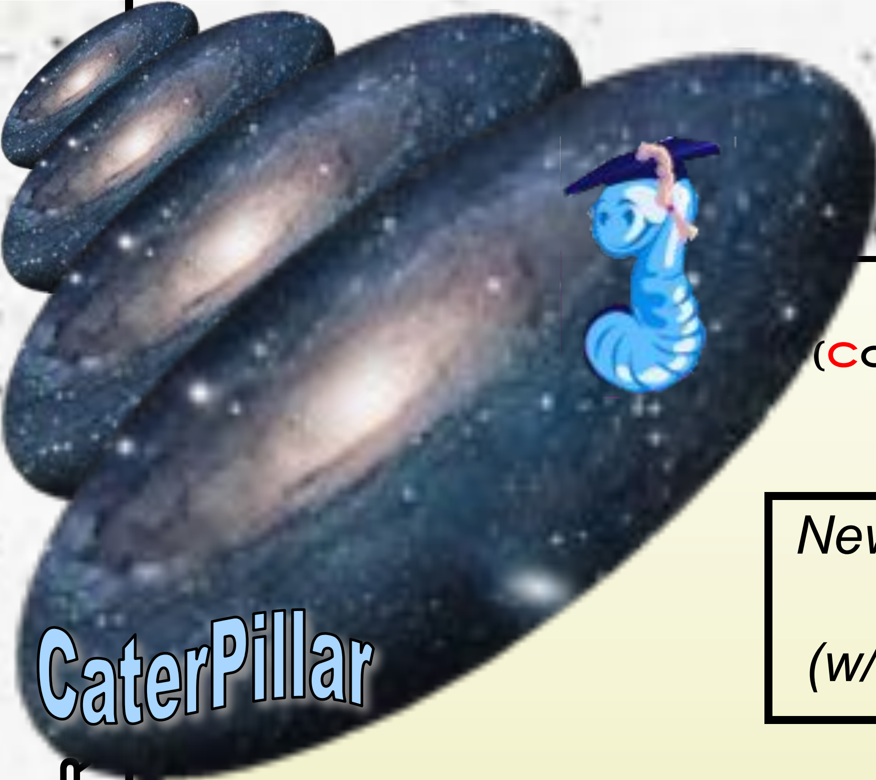
QUICK SUMMARY:

The Milky Way halo contains stars with exceptionally low metallicities

These stars are ~13 billion years old

They could come from small dwarf galaxies

CAN WE TRACE THE COSMOLOGICAL PATH OF THE MOST METAL-POOR STARS?



The CaterPillar Project

(Cosmology, galaxy Assembly & Time Evolution

-- a Research Pillar)

New DM-only simulation of up to ***100 of well resolved halos***

(w/ Gadget, new ICs & WMAP7 cosmology)

Anna Frebel (PI, MIT),
Ed Bertschinger (MIT),
Lars Hernquist (CfA),
Mark Vogelsberger (CfA),
Phillip Zukin (MIT,CfA, Berkeley)

Status:

Please see **Phillip Zukin's poster (P58)**

Motivation:

-Cosmic origin of the most metal-poor stars

-The Milky Way may be an outlier (i.e. Magellanic Clouds)

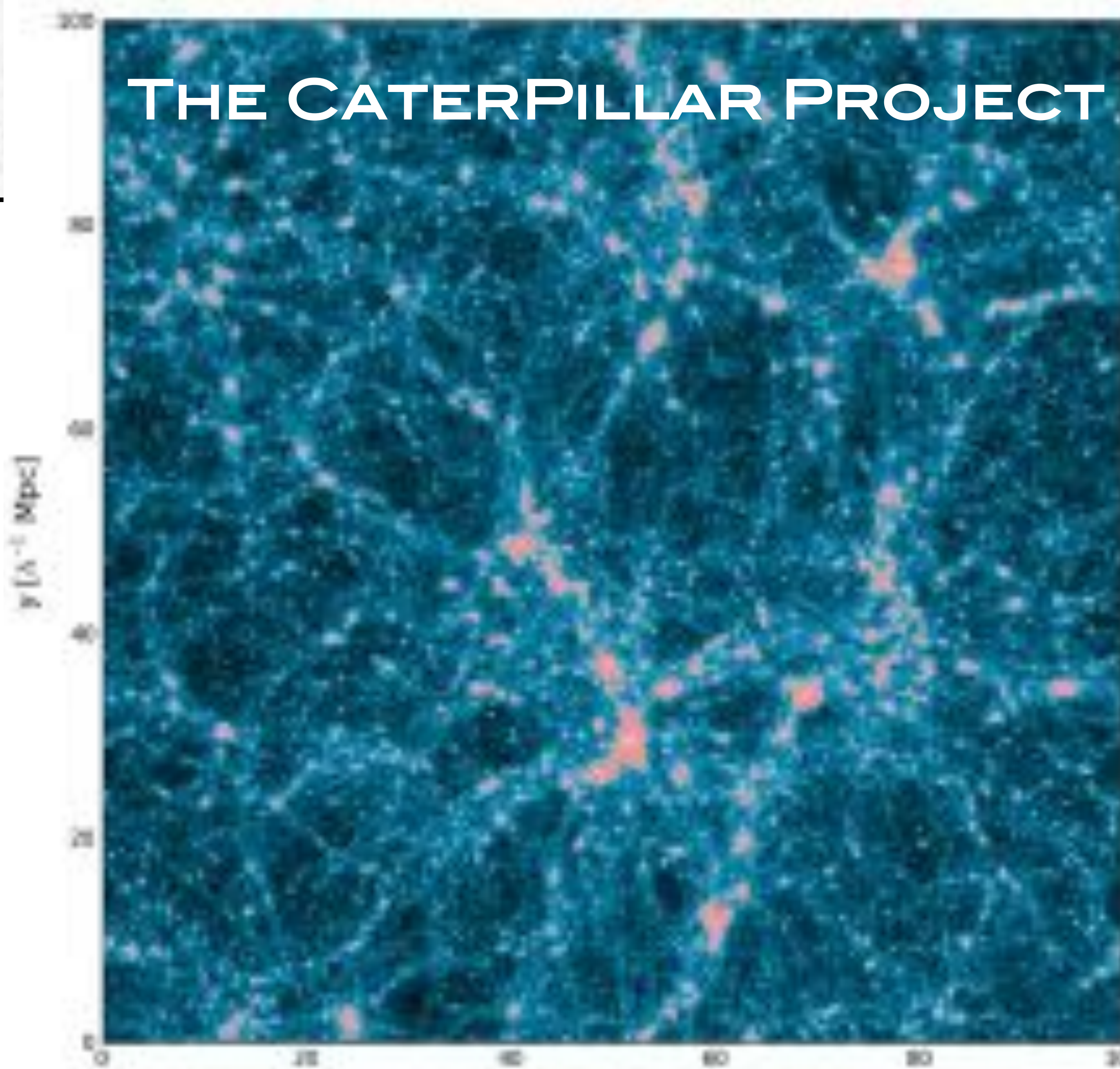
-Identifying the building blocks of the MW halo & especially those in ultra-faint dwarfs

-And of course much much more!

(We will make simulations available)

METAL-POOR STAR

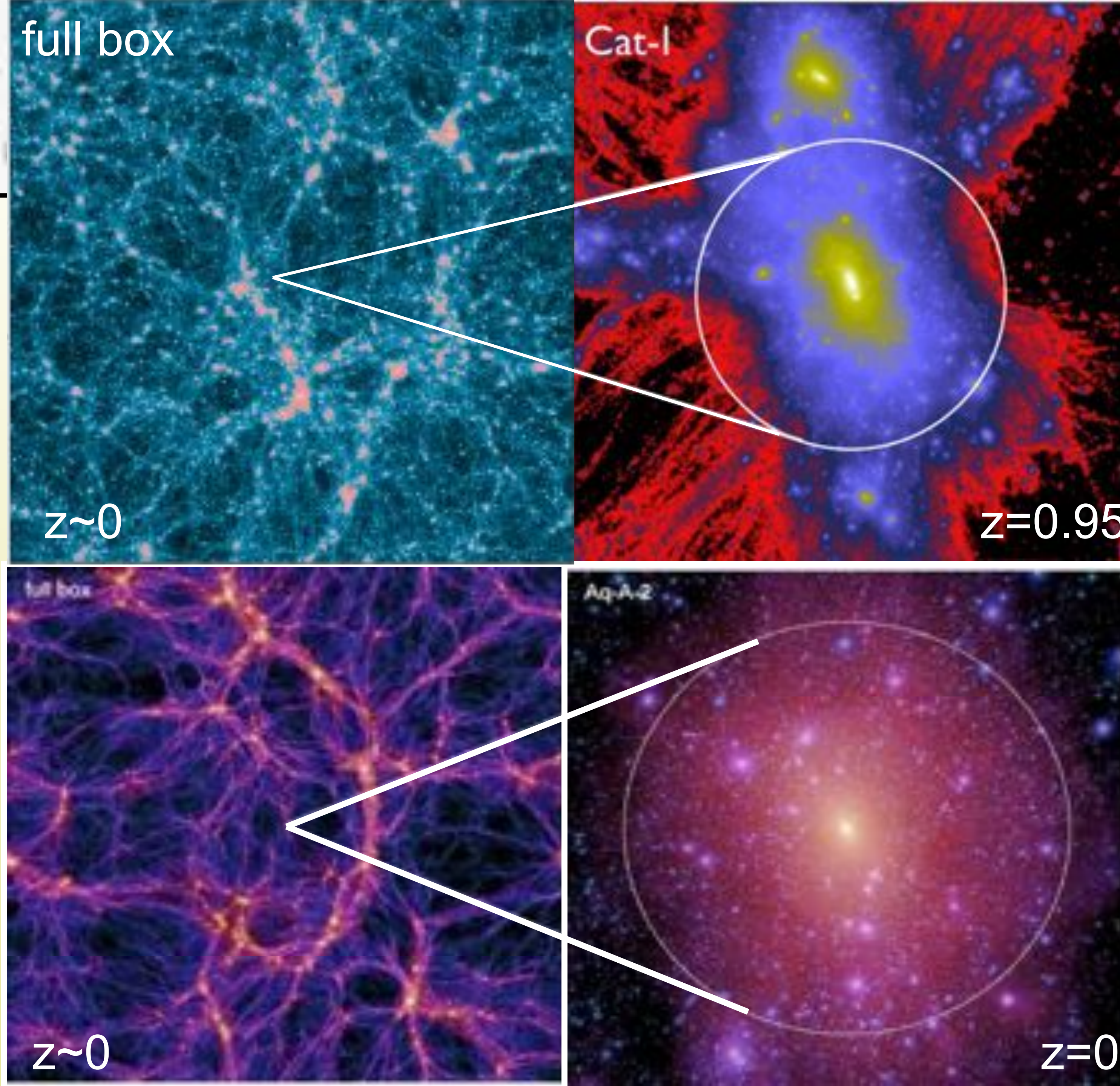
The CaterPillar Project



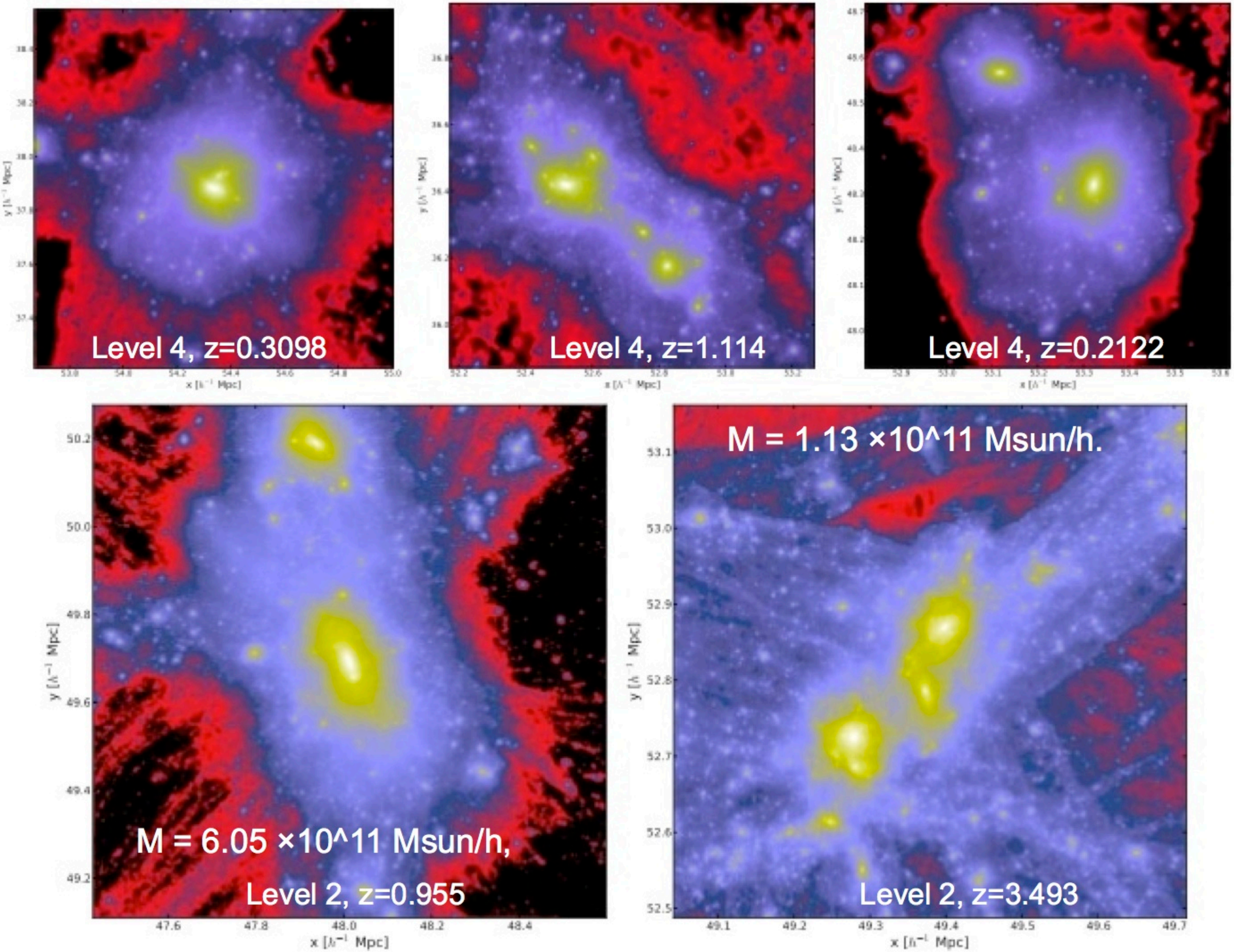
z = 0

CaterPillar

Aquarius



Level 4: min. particle mass = 3.9 x10^5 Msun/h   Level 2: min. particle mass = 1.1 x10^4 Msun/h



SUMMARY:

The Milky Way halo contains stars with exceptionally low metallicities

These stars are ~13 billion years old

They could come from small dwarf galaxies

With large cosmological simulations (+knowledge on SF, SNe, feedback, etc) we can better understand the MW halo formation and the origin of the most metal-poor stars

Little Diamonds in the sky…

"Old stars are a girl's best friend!"

The oldest stars are just like diamonds:

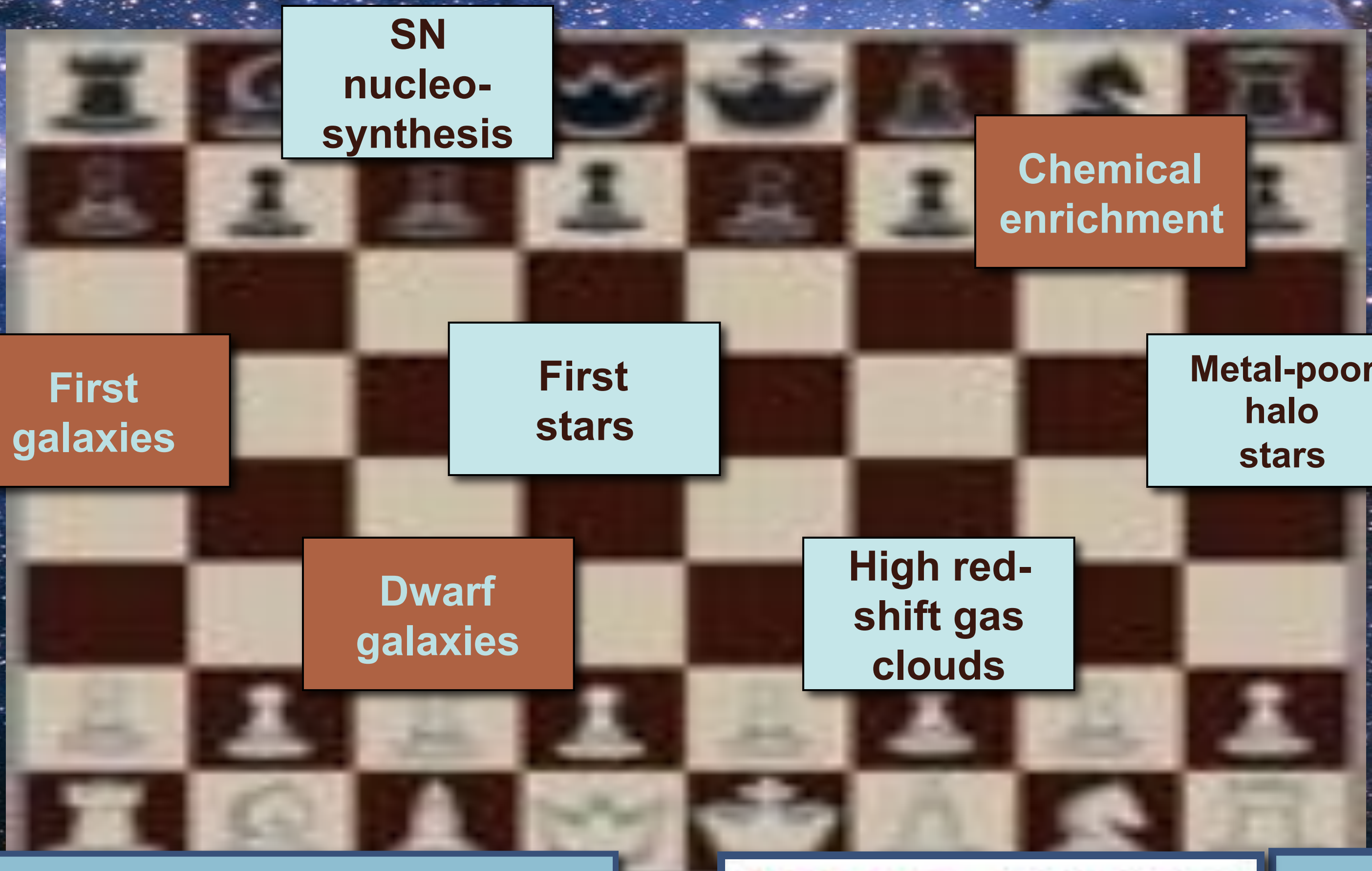
- They are rare
- They are difficult to come by
- They contain a lot of carbon
- They last (almost) forever
- They are good for many occasions/applications
- They make you happy!

Let's continue this treasure hunt !

Summer 2014

The Origin of the Elements

When, where, and how did they form?



Contact:
Anna Frebel & Rob Simcoe, MIT

Massachusetts Institute of Technology

Cambridge, MA, USA

Skymapper & Magellan: Match made in heaven

SkyMapper is taking data now!
Will provide more **metal-poor halo stars** as well as more **dwarf galaxies**!

1.3m Skymapper telescope
Siding Spring Observatory, Australia

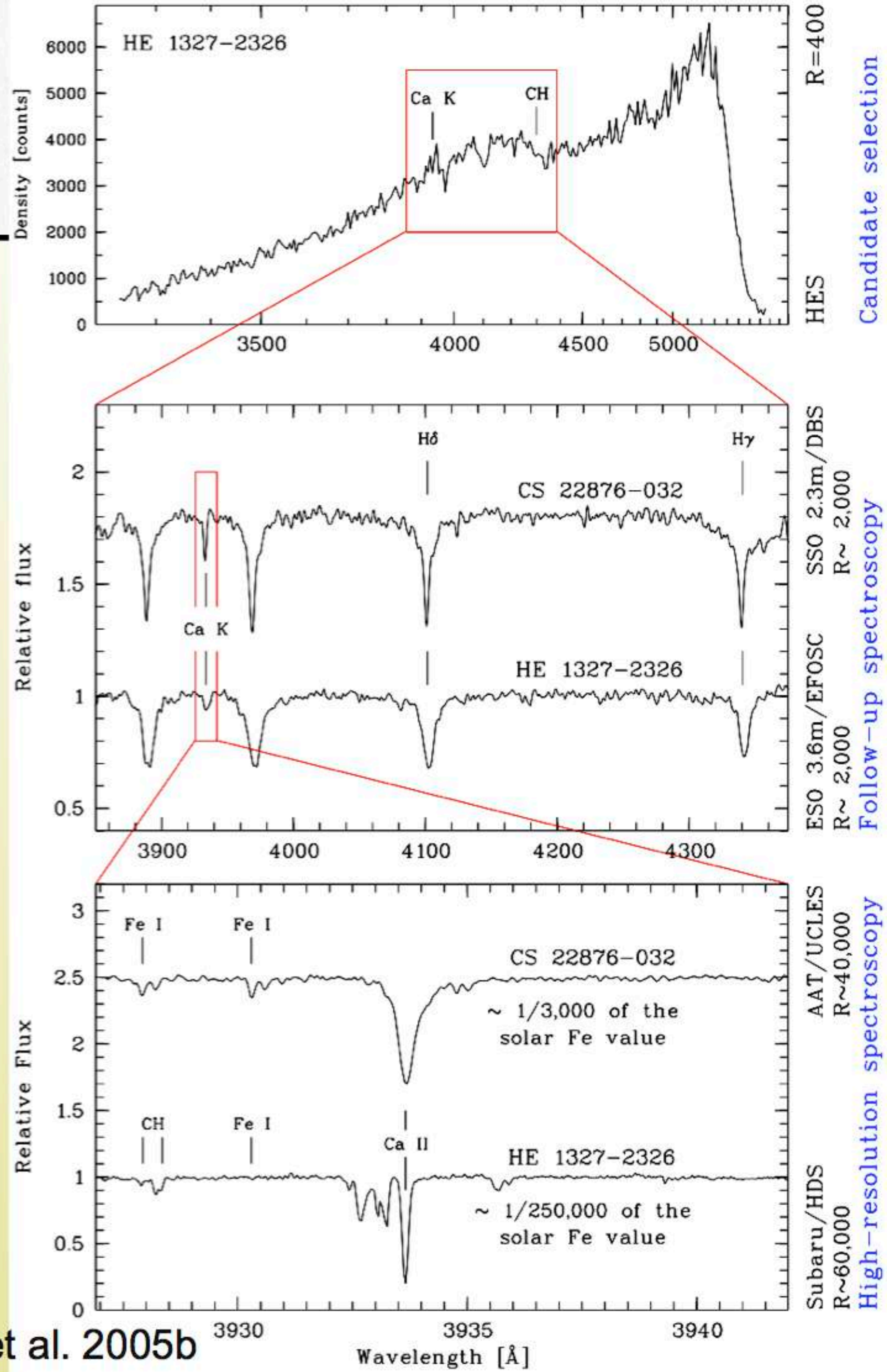
6.5m Magellan telescopes
Las Campanas Observatory, Chile

Three Observational Steps to Find Metal-Poor Stars

1. Sample selection and visual inspection based on spectra: Find appropriate candidates *(Ca scales with Fe!)*

2. Follow-up spectroscopy (medium resolution): Derive estimate for [Fe/H] from the Ca II K line

3. High-resolution spectroscopy: Detailed abundances analysis



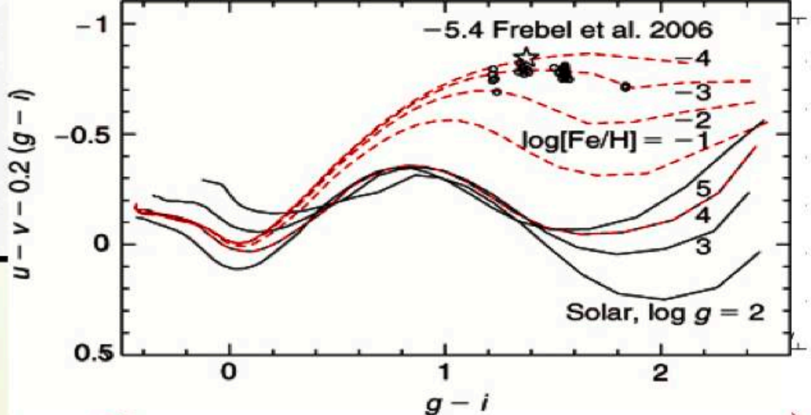
Frebel et al. 2005b

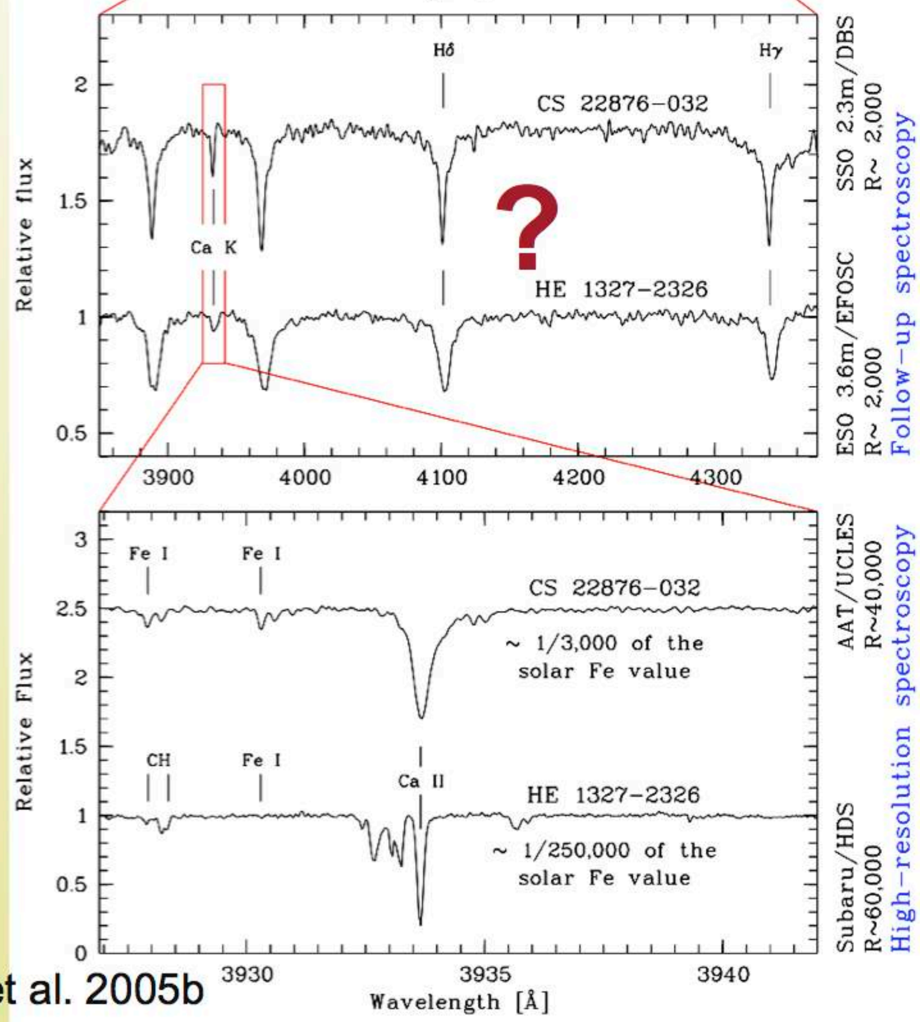
Metal-Poor Stars in SkyMapper

1. Sample selection and visual inspection based on several colors:
   Find appropriate candidates
   (Ca scales with Fe!)

2. Follow-up spectroscopy (medium resolution):
   Derive estimate for [Fe/H] from the Ca II K line

3. High-resolution spectroscopy:
   Detailed abundances analysis





Frebel et al. 2005b

ANNA FREBEL

MAPPING THE SOUTHERN SKY

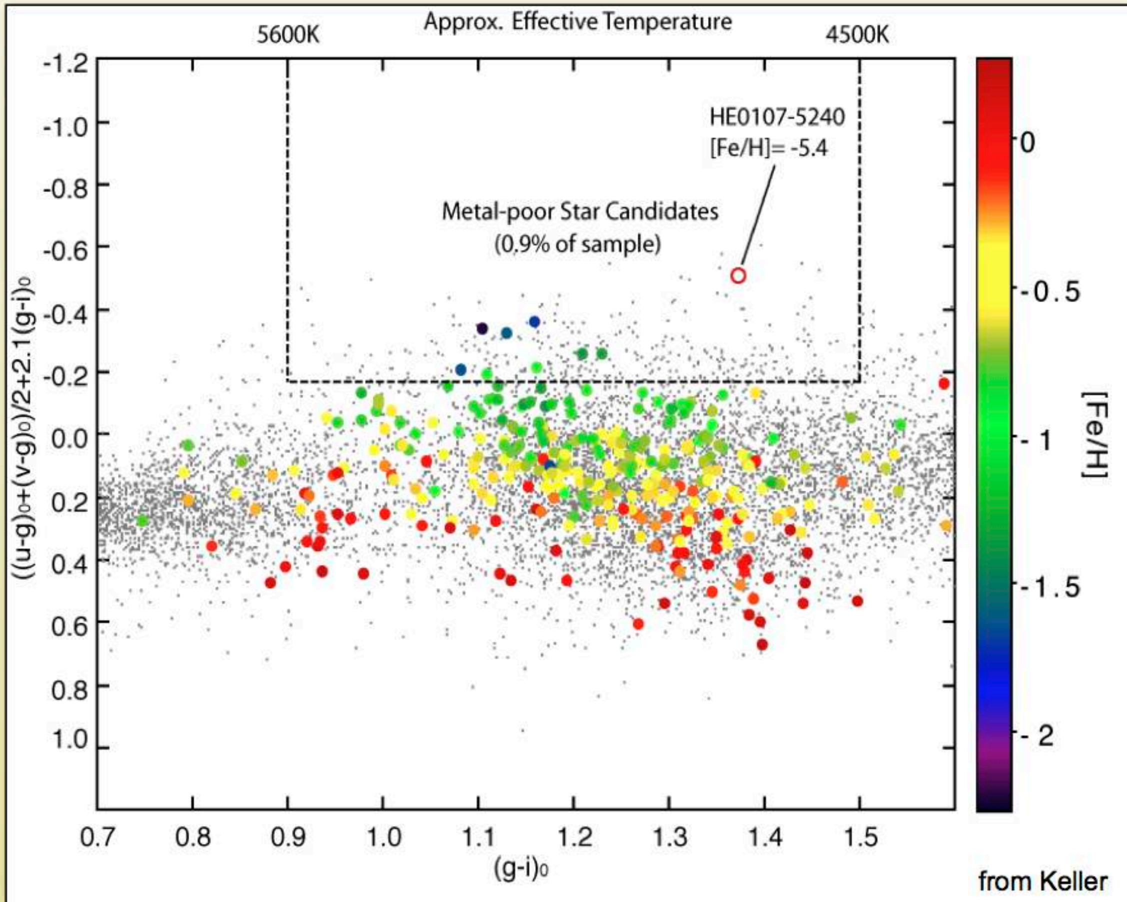
- New photometric technique to find metal-poor stars
- A survey of the South => **good census of most metal-poor stars**

=> **Limit on presence of most metal-poor stars/PopIII low-mass stars**

We have taken
test data already:
=> **[Fe/H] ~ -3.5 binary**

SkyMapper EMP program
with Magellan telescope

Color code based on
AAT/AEGIS follow-up
med-res spectroscopy



from Keller

METAL-POOR STARS

TEXTBOOK: PLANETS, STARS & STELLAR SYSTEMS

<u>Volume 5: STELLAR POPULATIONS</u>

Editor: Gerry Gilmore; to appear in 2012, by Springer

Metal-poor stars and the chemical enrichment of the universe

(by Anna Frebel & John Norris, arXiv:1102.1748 => free :)

Abundance compilation of metal-poor stars in the literature:

~1000 stars with chemical abundances (halo and dwarf galaxies)

See https://www.space.mit.edu/~afrebel/abundances/abund.html

(as part of Frebel 2010, review on metal-poor stars in halo & dwarfs)

There is also Suda-san's **SAGA database** (Suda+07)