

# The first generation stars

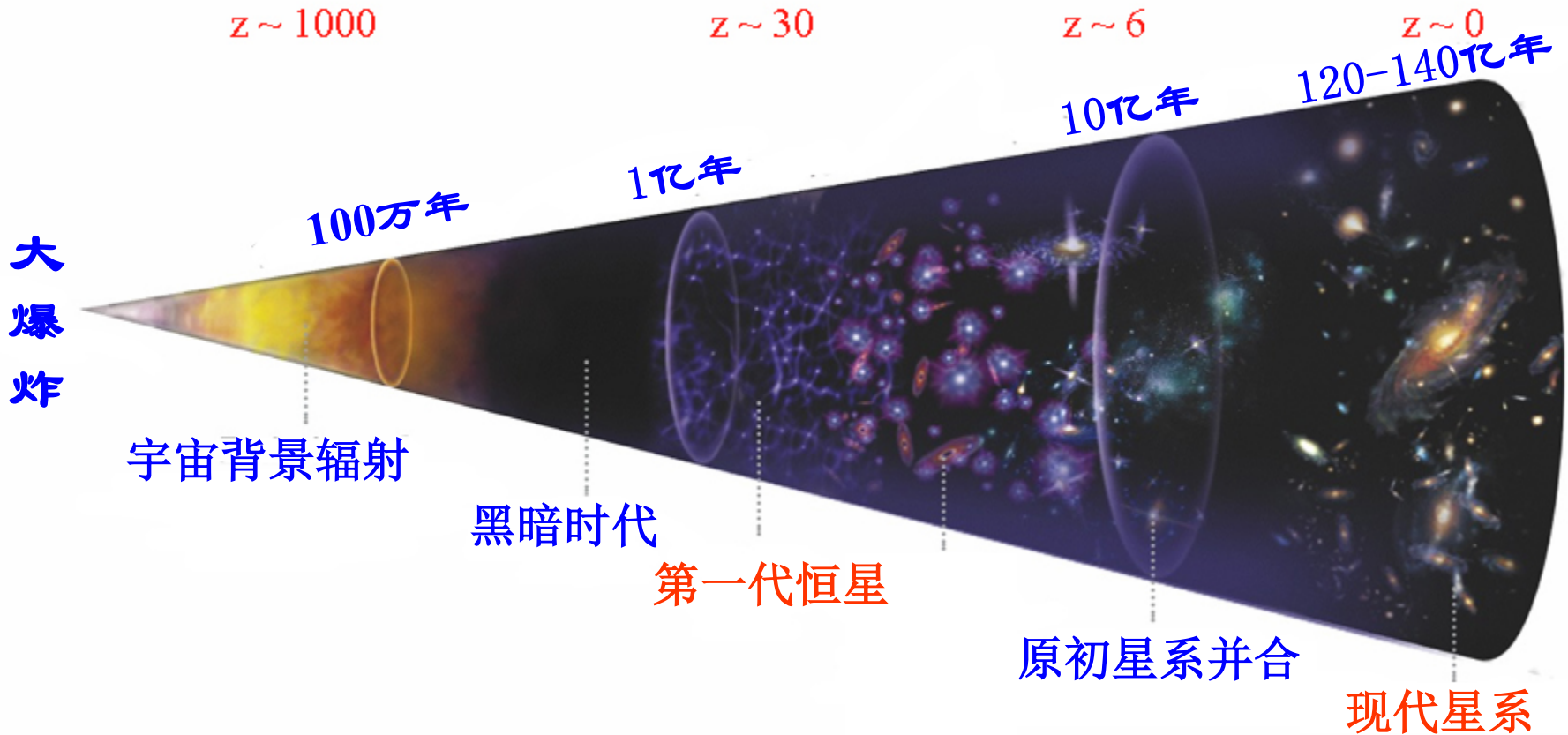
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# History of the Universe

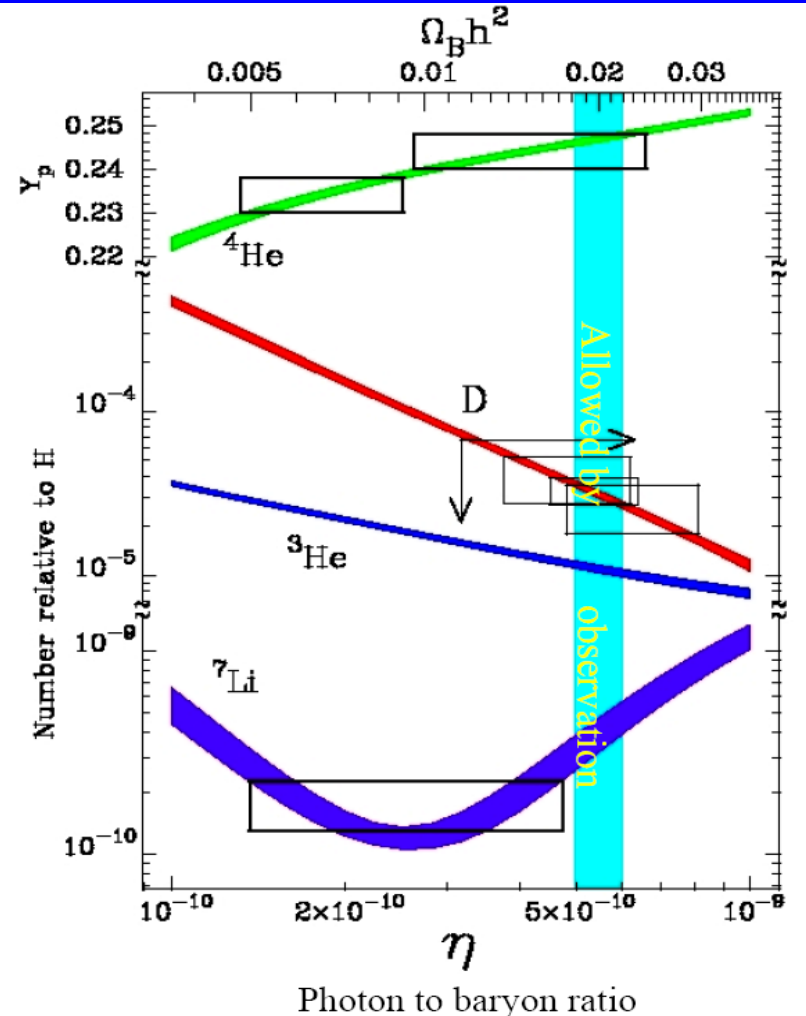


# BBN: Big Bang nucleosynthesis

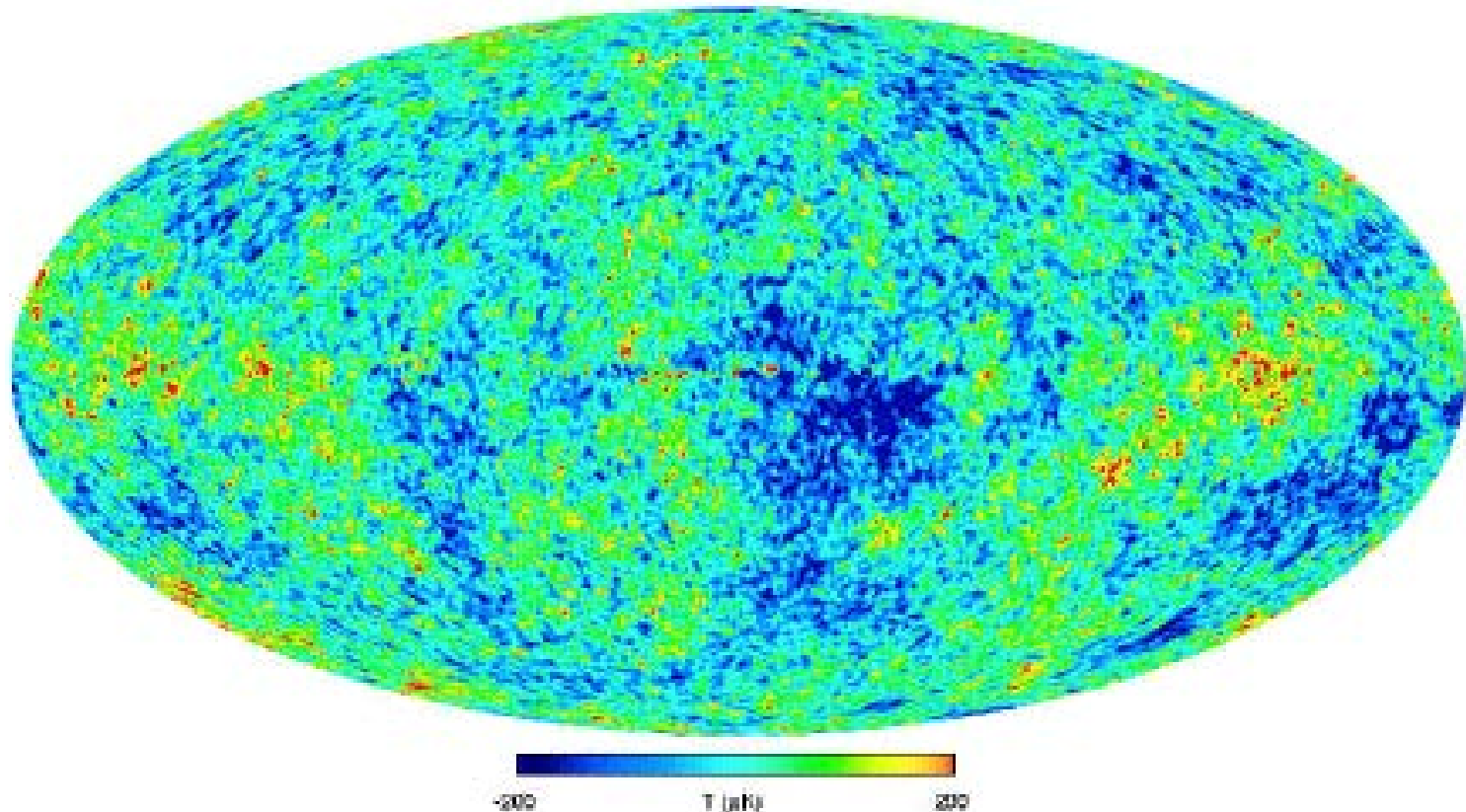
$^1\text{H}$   
 $^2\text{H}$   
 $^3\text{He}$   
 $^4\text{He}$   
 $^7\text{Li}$

- During the very first 3 minutes the Universe "cools" to  $10^9\text{ C}$
- The nuclei of a few light elements are formed
  - Hydrogen ( $^1\text{H}$ ,  $^2\text{H}$ )
  - Helium ( $^3\text{He}$ ,  $^4\text{He}$ )
  - Lithium ( $^7\text{Li}$ )
- All the other elements formed later through nuclear reactions in stars and stellar explosions

The atoms in our bodies were made in stars



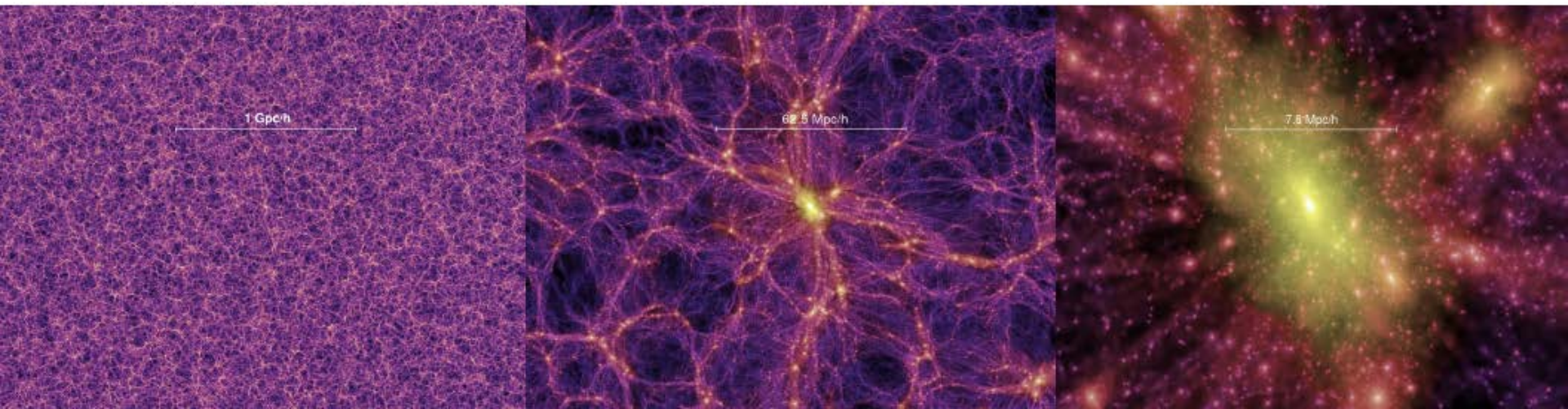
# The *WMAP* of the Cosmic Microwave Background



Temperatures fluctuate by  $\pm 200 \mu\text{K}$  around a mean of  $2.73 \text{ K}$

# Visualizing Darkness

- The smooth becomes rough with the passing of time
- Uniformity, filamentarity, hierarchy – it all depends on scale
- A short tour of the Universe



*Simulation:*  
 $Z=17$   
 $\sim 10^8 \text{ yr}$

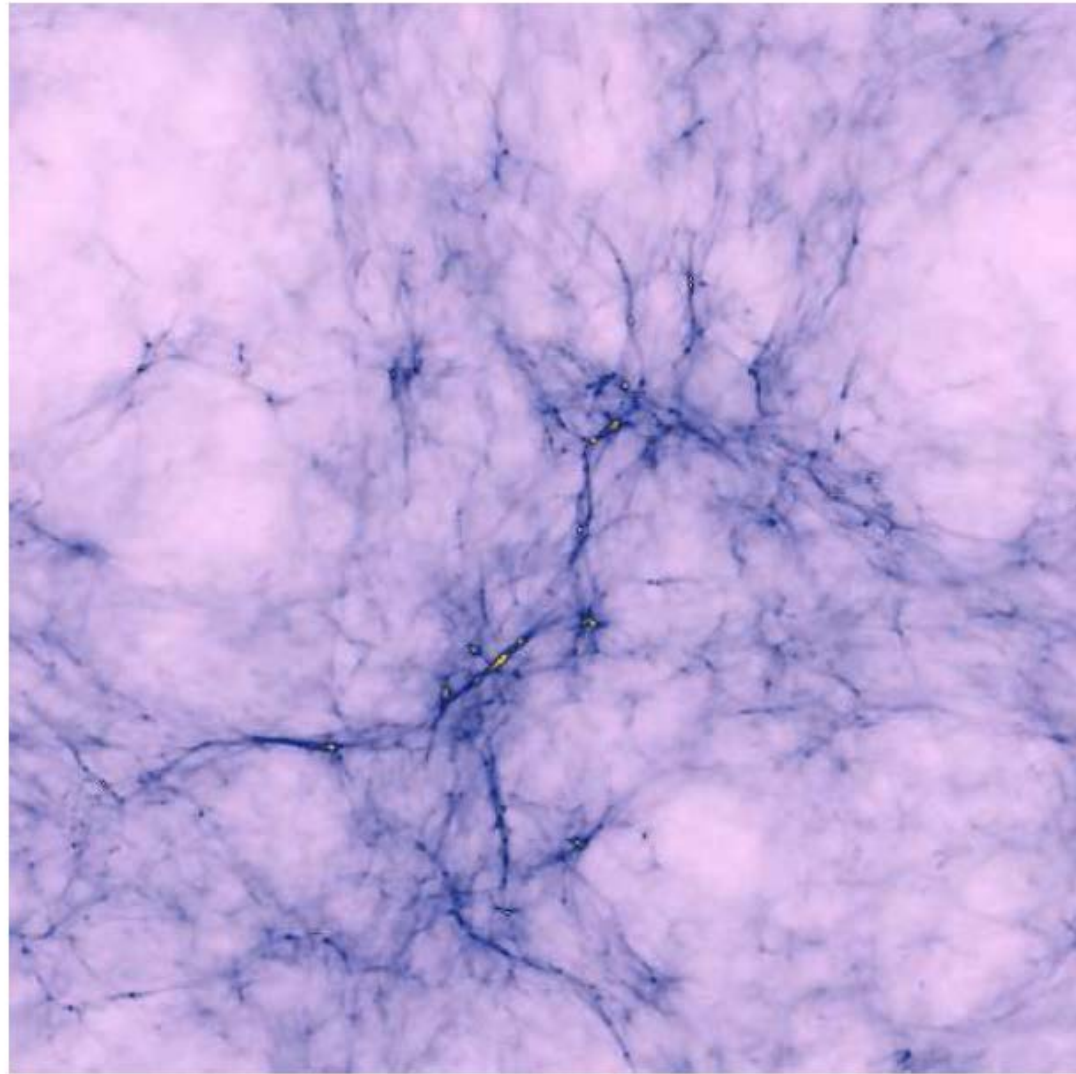
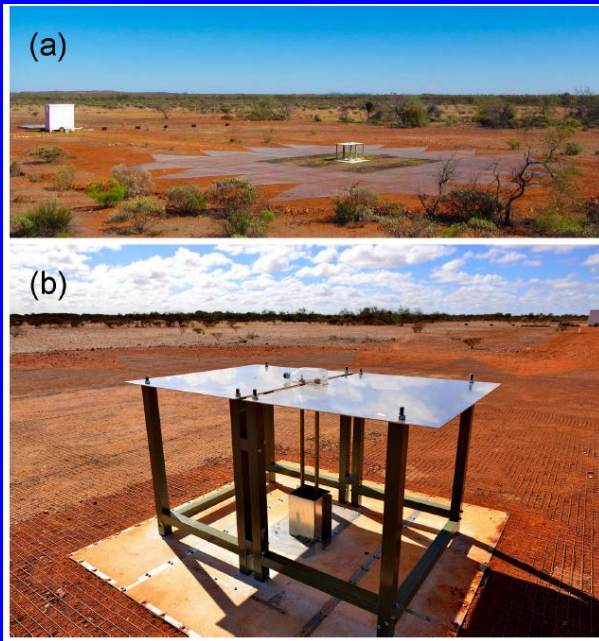
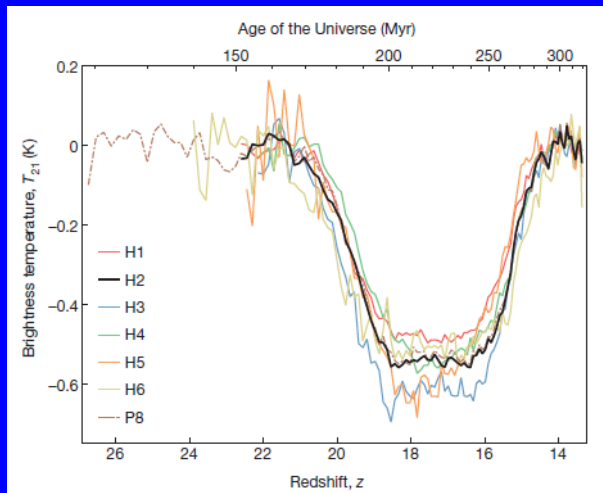


Figure 1: Emergence of primordial star forming regions within a standard  $\Lambda$ CDM cosmology. Shown is the projected gas density at  $z = 17$  within a simulation box of physical size  $\sim 50$  kpc. The bright knots at the intersections of the filamentary network are the sites where the first stars form. (From Yoshida et al. 2003a.)

# Bowman et al., 2018, Nature, 555, 67



- HI 21cm (1420MHz) hyperfine line
- 78MHz  $\Rightarrow Z \approx 17 \Rightarrow \sim 220$ Myr after Big Bang
- After stars formed in the early universe, their UV light is expected to have penetrated the primordial H gas and altered the excitation state of its 21 cm line



# First Stars

- Primordial pristine gas (H, He, small Li)
- Star formation began no more than a **few hundred million years** after Big Bang.
- The first stars could be born only from a gas having the chemical composition inherited from Big Bang was inescapable.

- The first generation of stars had **important effects** on subsequent galaxy formation.
  - First stars produced copious amounts of UV photons to **reionize** the universe.
  - The SN explosions that ended the lives of the first stars were responsible for the initial **enrichment** of the IGM with heavy elements.

- Even if such stars were not observed, they were already named:

population III stars.

## Two Populations of Stars: Pop I and Pop II.

**Pop I** stars are **younger**, formed as a **later generation**, and have **higher metal content**.

**Pop II** stars are **older**, formed in **early generation**, and have **lower metal content**.

**Pop I** stars are located in the **galaxy disk** where stars are continually forming.

**Pop II** stars are located in the **bulge, halo, and globular clusters**.

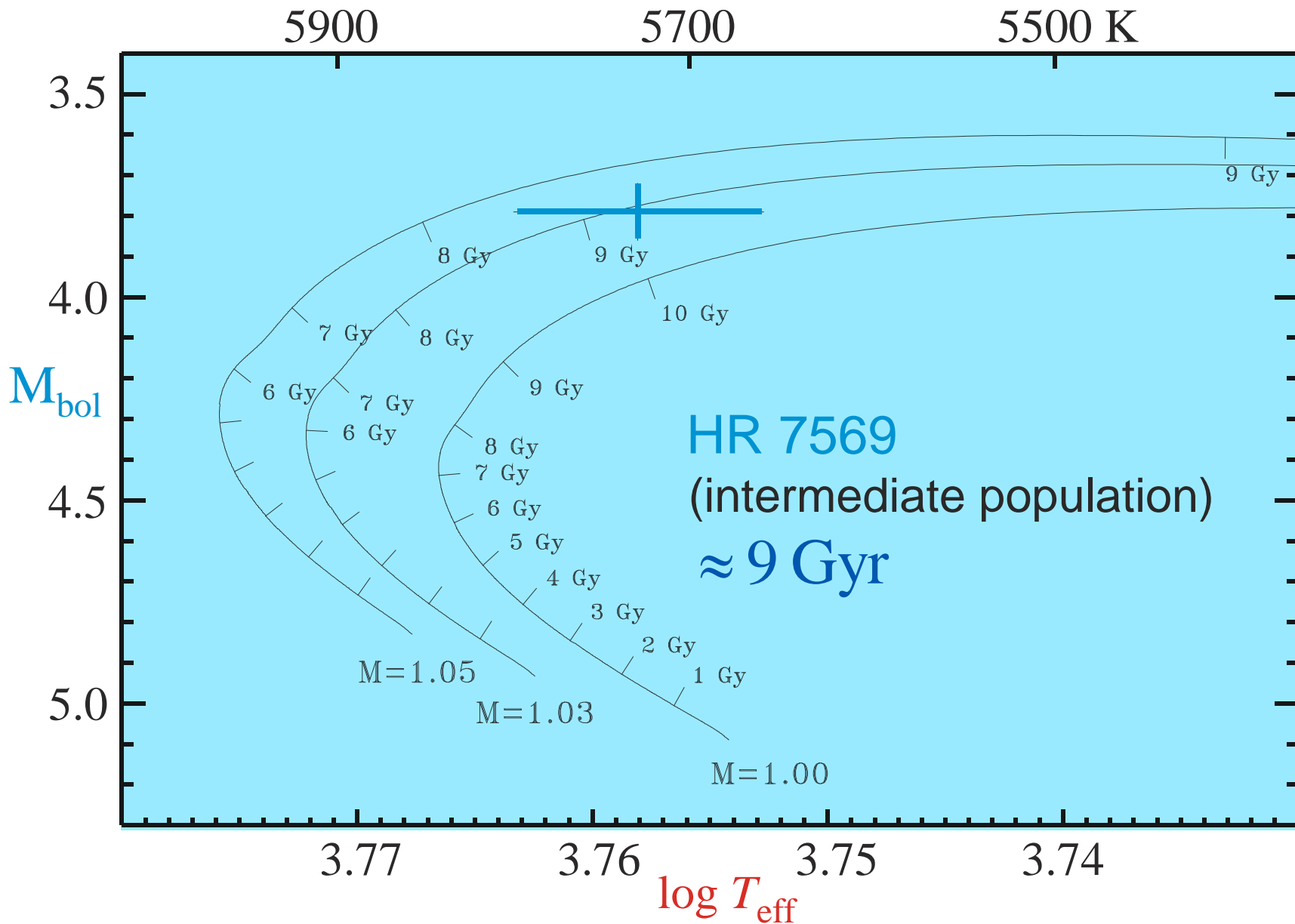
Property	<b>Pop I</b>		<b>Pop II</b>	
	<i>Extreme</i>	<i>Intermediate</i>	<i>Intermediate</i>	<i>Extreme</i>
Location	Spiral Arms	Disk	Bulge	Halo
Metals (%)	3	1.6	0.8	<0.8
Orbit shape	circular	slight elliptical	moderate elliptical	highly elliptical
Average Age (yrs)	100 million and younger	0.2-10 billion	2-10 billion	10-14 billion

# Search for Pop III stars

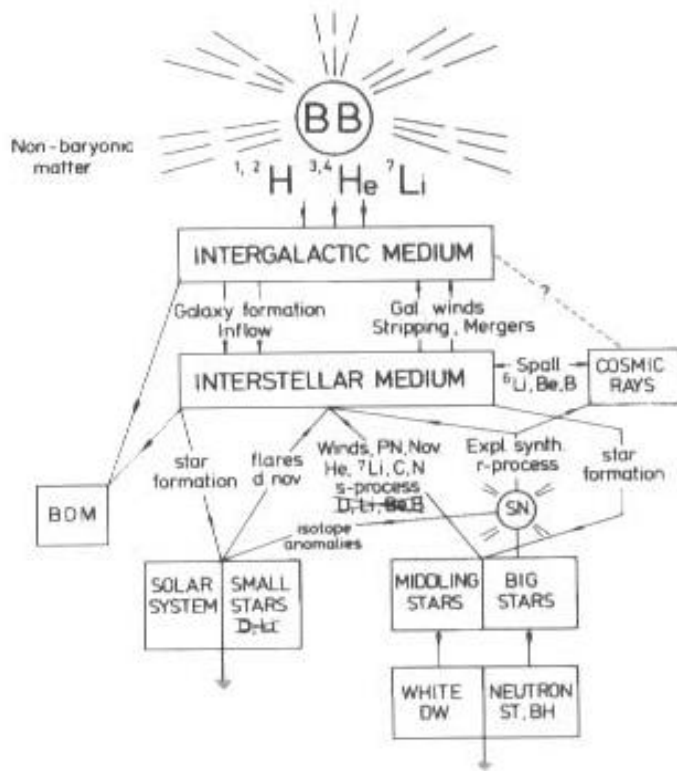
- The quest for population III stars has fascinated astronomers for many decades, going back to the first tentative ideas of Schwarzschild & Spitzer (1953).
- Recently, the subject has attracted an increased interest, both from a theoretical and observational perspective.

# Age?

- At first view one could think of determining the age of a great number of stars and selecting the very **oldest** ones.
- Actual surveys of first generation stars are **not** based on this principle.
- The reason is that the method can be applied only to clusters of stars, the age of individual stars of unknown **distance** not being obtainable with need accuracy.



# Metallicity !



- Except for the lightest elements, the history of the chemical compositions of the Galaxy is dominated by nucleosynthesis occurring in many generations of stars.

# 宇宙中各类元素的来源：炼金术？

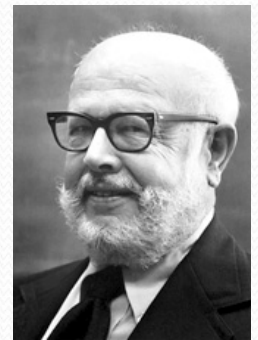


# 元素核合成: B<sup>2</sup>FH理论 (1957)

- Hydrogen burning
- Helium burning
- The  $\alpha$  process
- The e process
- The s process
- The r process
- The p process
- The x process

➤ D, He<sup>?</sup>, Be, B

Burbidge 夫妇  
Fowler, W.  
Hoyle, F.



1983年, W.A. Fowler因“对宇宙中形成化学元素的核反应的理论实验研究”获诺贝尔物理奖。

# 元素周期表

周期	电子层	I A											0						
1	K	1 氢 H $1s^1$ 1.008											2 氦 He $1s^2$ 20.18						
2	L K 2	3 锂 Li $2s^1$ 6.941	4 铍 Be $2s^2$ 9.012											10 氖 Ne $2s^2 2p^6$ 20.18					
3	M L K 2	11 钠 Na $3s^1$ 22.99	12 镁 Mg $3s^2$ 24.31	III B	IV B	V B	VI B	VII B	VIII	I B	II B	13 铝 Al $3s^2 3p^1$ 26.98	14 硅 Si $3s^2 3p^2$ 28.09	15 磷 P $3s^2 3p^3$ 30.97	16 硫 S $3s^2 3p^4$ 32.06	17 氯 Cl $3s^2 3p^5$ 35.45	18 氩 Ar $3s^2 3p^6$ 39.95		
4	N M L K 2	19 钾 K $4s^1$ 39.10	20 钙 Ca $4s^2$ 40.08	21 钪 Sc $3d^1 4s^2$ 44.96	22 钛 Ti $3d^2 4s^2$ 47.88	23 钒 V $3d^3 4s^2$ 50.94	24 铬 Cr $3d^5 4s^1$ 52.00	25 锰 Mn $3d^5 4s^2$ 54.94	26 铁 Fe $3d^6 4s^2$ 55.85	27 钴 Co $3d^7 4s^2$ 58.93	28 镍 Ni $3d^8 4s^2$ 58.69	29 铜 Cu $3d^{10} 4s^1$ 63.55	30 锌 Zn $3d^{10} 4s^2$ 65.38	31 镓 Ga $4s^2 4p^1$ 69.72	32 锗 Ge $4s^2 4p^2$ 72.59	33 砷 As $4s^2 4p^3$ 74.92	34 硒 Se $4s^2 4p^4$ 78.96	35 溴 Br $4s^2 4p^5$ 79.90	36 氪 Kr $4s^2 4p^6$ 83.80
5	O N M L K 2	37 铷 Rb $5s^1$ 85.47	38 锶 Sr $5s^2$ 87.62	39 钇 Y $4d^1 5s^2$ 88.91	40 锆 Zr $4d^2 5s^2$ 91.22	41 铌 Nb $4d^4 5s^1$ 92.91	42 钼 Mo $4d^5 5s^1$ 95.94	43 锝 Tc $4d^5 5s^2$ [98]	44 钌 Ru $4d^7 5s^1$ 101.1	45 铑 Rh $4d^8 5s^1$ 102.9	46 钯 Pd $4d^{10}$ 106.4	47 银 Ag $4d^9 5s^1$ 107.9	48 镉 Cd $4d^{10} 5s^2$ 112.4	49 铟 In $5s^2 5p^1$ 114.8	50 锡 Sn $5s^2 5p^2$ 118.7	51 锑 Sb $5s^2 5p^3$ 121.8	52 碲 Te $5s^2 5p^4$ 127.6	53 碘 I $5s^2 5p^5$ 126.9	54 氙 Xe $5s^2 5p^6$ 131.3
6	P O N M L K 2	55 铯 Cs $6s^1$ 132.9	56 钡 Ba $6s^2$ 137.3	57-71 镧系 La-Lu	72 铪 Hf $5d^2 6s^2$ 178.5	73 钽 Ta $5d^3 6s^2$ 180.9	74 钨 W $5d^4 6s^2$ 183.9	75 铼 Re $5d^5 6s^2$ 186.2	76 锇 Os $5d^6 6s^2$ 190.2	77 铱 Ir $5d^7 6s^2$ 192.2	78 铂 Pt $5d^9 6s^1$ 195.1	79 金 Au $5d^{10} 6s^1$ 197.0	80 汞 Hg $5d^{10} 6s^2$ 200.6	81 铊 Tl $6s^2 6p^1$ 204.4	82 铅 Pb $6s^2 6p^2$ 207.2	83 铋 Bi $6s^2 6p^3$ 209.0	84 钋 Po $6s^2 6p^4$ [209]	85 砒 At $6s^2 6p^5$ [210]	86 氡 Rn $6s^2 6p^6$ [222]
7	Q P O N M L K 2	87 钫 Fr $7s^1$ [223]	88 镭 Ra $7s^2$ 226.0	89-103 锕系 Ac-Lr	104	105	106	107	108	109									

注:

- 原子量以碳-12原子质量的1/12为基准。
- 元素印红色的为放射性元素。
- 原子序数旁印  $\circ$  的为人工元素。

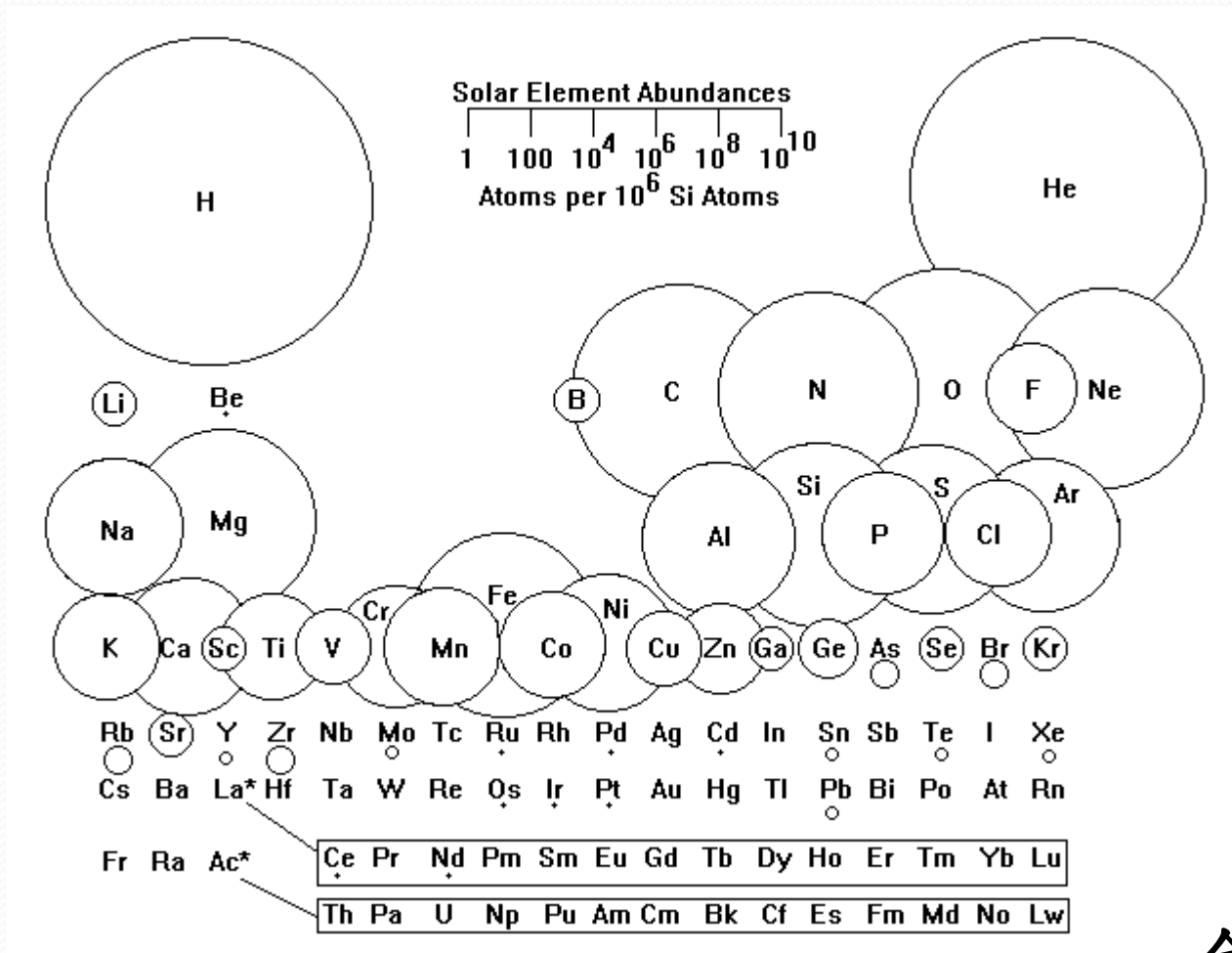
原子序数 → 26 铁 ← 元素名称

元素符号 → Fe ← 外国电子层排布, 加括号的指可能的电子层排布

↑  
原子量 (有括号的为半衰期最长的同位素的质量数)

57-71 镧系元素	57 镧 La $5d^1 6s^2$ 138.9	58 铈 Ce $4f^1 5d^1 6s^2$ 140.1	59 镨 Pr $4f^3 6s^2$ 140.9	60 钕 Nd $4f^4 6s^2$ 144.2	61 钷 Pm $4f^5 6s^2$ [145]	62 钐 Sm $4f^6 6s^2$ 150.4	63 铕 Eu $4f^7 6s^2$ 152.0	64 钆 Gd $4f^7 5d^1 6s^2$ 157.3	65 铽 Tb $4f^9 6s^2$ 158.9	66 镱 Dy $4f^{10} 6s^2$ 162.5	67 铈 Ho $4f^{11} 6s^2$ 164.9	68 铒 Er $4f^{12} 6s^2$ 167.3	69 铥 Tm $4f^{13} 6s^2$ 168.9	70 镱 Yb $4f^{14} 6s^2$ 173.0	71 镱 Lu $4f^{14} 5d^1 6s^2$ 175.0
89-103 锕系元素	89 锕 Ac $6d^1 7s^2$ 227.0	90 钍 Th $6d^2 7s^2$ 232.0	91 镤 Pa $5f^2 6d^1 7s^2$ 231.0	92 铀 U $5f^3 6d^1 7s^2$ 238.0	93 镎 Np $5f^4 6d^1 7s^2$ 237.0	94 钚 Pu $5f^6 7s^2$ [244]	95 镅 Am $5f^7 7s^2$ [243]	96 锔 Cm $5f^7 6d^1 7s^2$ [247]	97 锫 Bk $5f^9 7s^2$ [247]	98 锿 Cf $5f^{10} 7s^2$ [251]	99 镱 Es $5f^{11} 7s^2$ [252]	100 镆 Fm $5f^{12} 7s^2$ [257]	101 钷 Md $(5f^{13} 7s^2)$ [258]	102 诺 No $(5f^{14} 7s^2)$ [259]	103 铹 Lr $(5f^{14} 6d^1 7s^2)$ [260]

# 太阳元素丰度

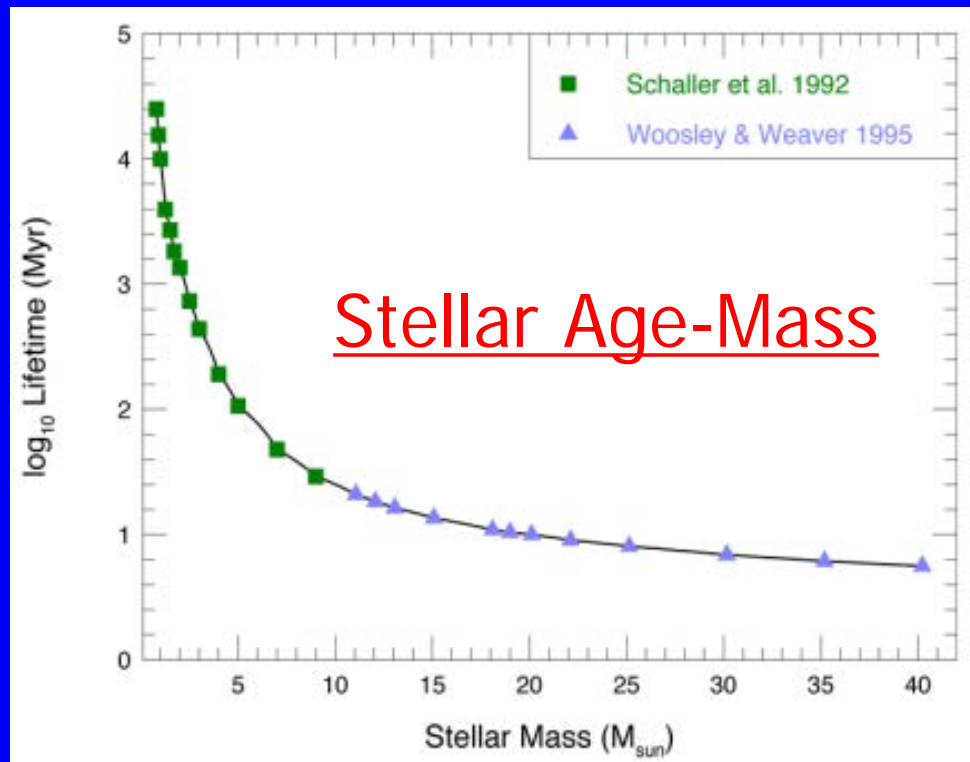


Metal: all elements except H & He

金属丰度  
铁丰度

# Low mass stars ( $M < 0.9 M_{\odot}$ )

- Stars of low mass have **long lifetimes**, some comparable to the age of the Galaxy.

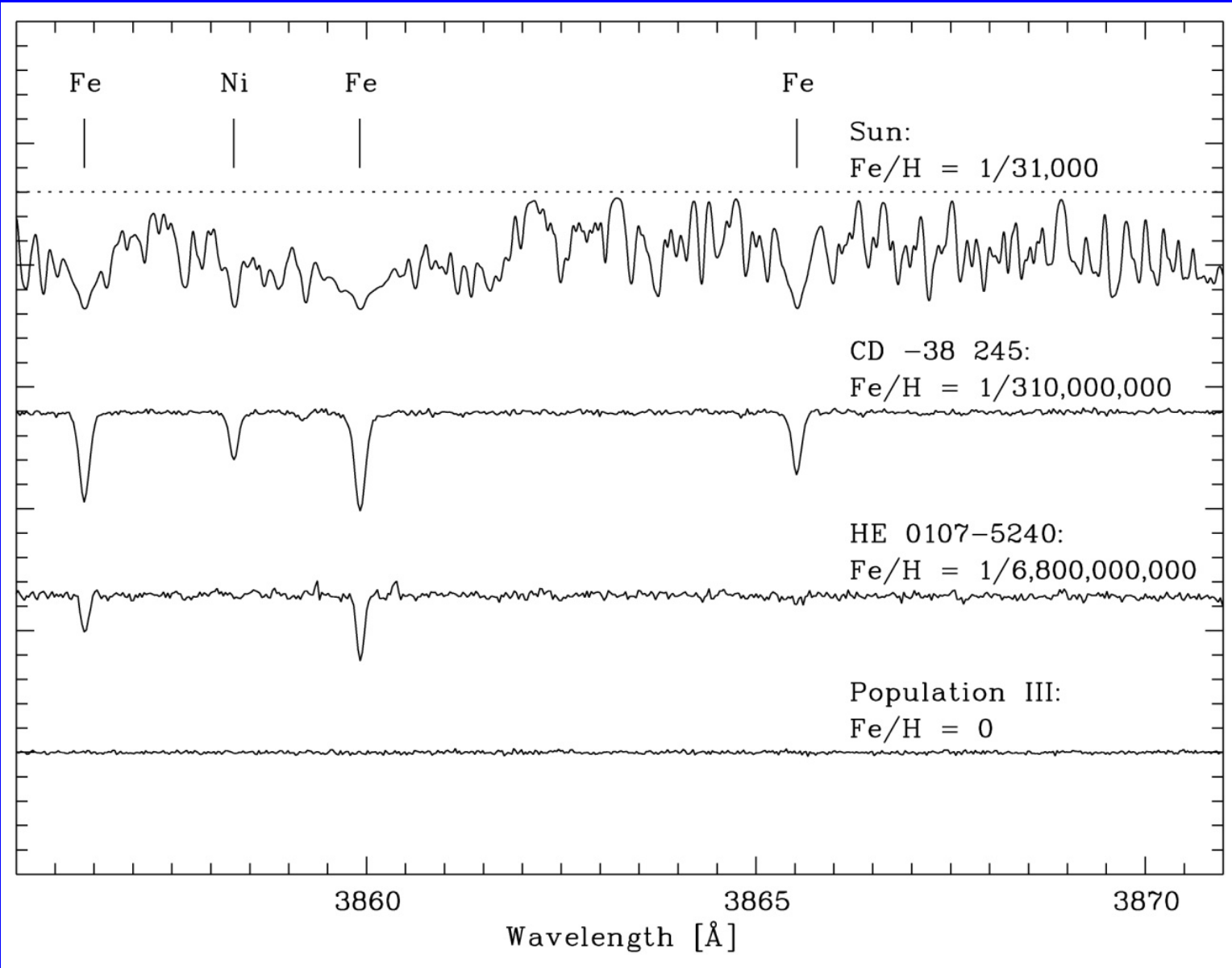


- Their envelopes have preserved much of their **original chemical composition**.
- They are *fossils* containing information about the history of the evolution of chemical abundances in the Galaxy.



t

# Galactic chemical evolution



# Preliminary definitions:

- $\log \varepsilon (A) \equiv \log_{10}(N_A/N_H)+12.0$
- $[Fe/H] \equiv \log_{10}(N_{Fe}/N_H)_* - \log_{10}(N_{Fe}/N_H)_{\odot}$
- $[A/B] \equiv \log_{10}(N_A/N_B)_* - \log_{10}(N_A/N_B)_{\odot}$

# Beers & Christlieb(2005)

[Fe/H]	Term	Acronym
$> +0.5$	Super metal-rich	SMR
$\sim 0.0$	Solar	—
$< -1.0$	Metal-poor	MP
$< -2.0$	Very metal-poor	VMP
$< -3.0$	Extremely metal-poor	EMP
$< -4.0$	Ultra metal-poor	UMP
$< -5.0$	Hyper metal-poor	HMP
$< -6.0$	Mega metal-poor	MMP

## Note that:

- $[\text{Fe}/\text{H}]$  does **not** necessarily refer to the **total metal content** of a given stellar atmosphere, which might not in fact be significantly less than the solar value, when the star under consideration also exhibits large overabundances of elements such as C, N, and O.

# How can we find metal-poor stars?

Metal-poor stars can best be identified in the halo of the Galaxy.

Problems:

- Metal-poor stars are very rare!  
In the halo, approximately
    - one out of ~1000 stars has  $[Fe/H] < -2.0$
    - one out of ~10,000 stars has  $[Fe/H] < -3.0$ .
  - They are difficult to recognize; especially very metal-poor stars (i.e., stars with  $[Fe/H] < -2.0$ ).
- => Wide-angle surveys



# Five ways:

- Informed **serendipity**
- Systematic surveys of **high-proper motion** stars
- Systematic **objective prism** surveys for weak-lined objects with **Schmidt telescopes**
- **Multi-fiber** spectroscopic survey
- **Photometric** surveys

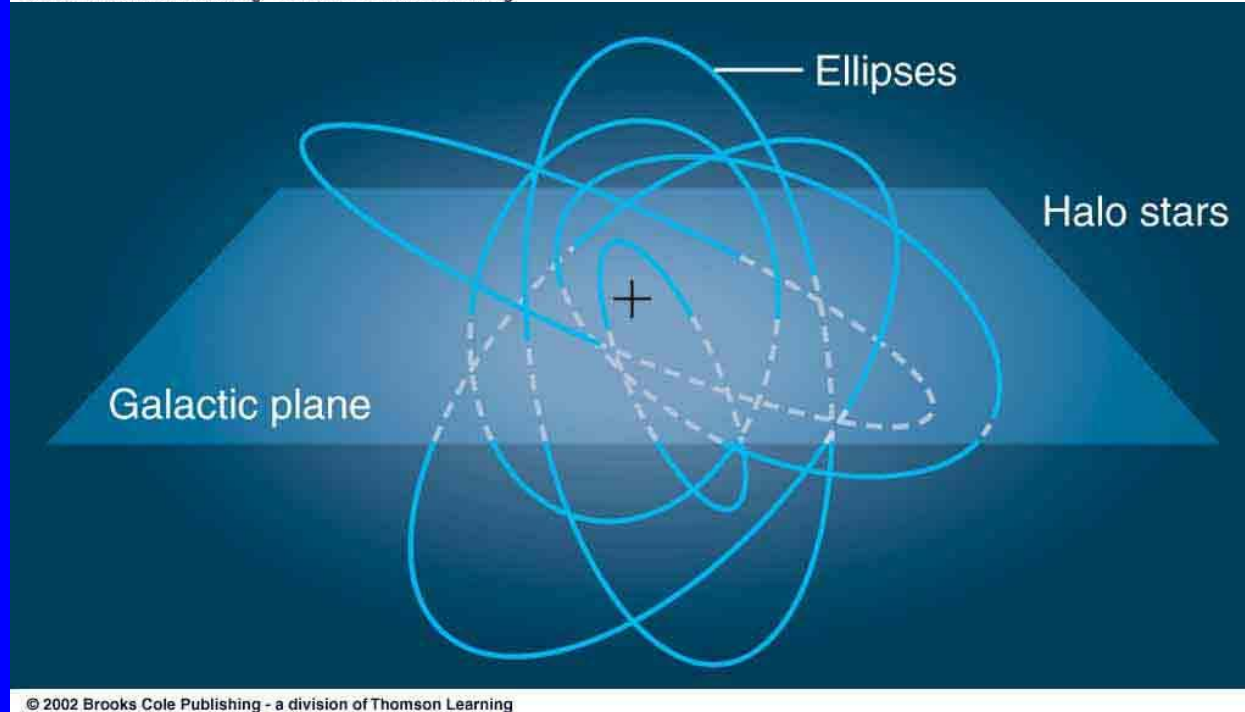
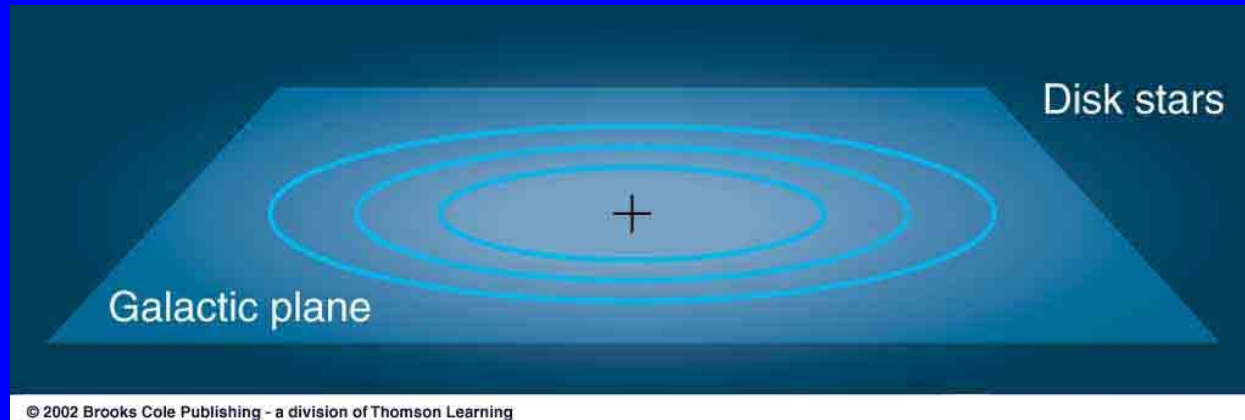
# 1. Informed serendipity:

- CD-38°245:  $[\text{Fe}/\text{H}]=-4.0$   
search for A stars at South Galactic Pole
- G64-12:  $[\text{Fe}/\text{H}]=-3.2$   
extremely high space velocity

## 2. High proper motion surveys:

- Connection between the velocities of star and their abundance
- Systematically study objects that exhibited the largest measured proper motions

The motions of disk stars are in a plane.  
The motion of Halo stars and clusters are elliptical about the center.

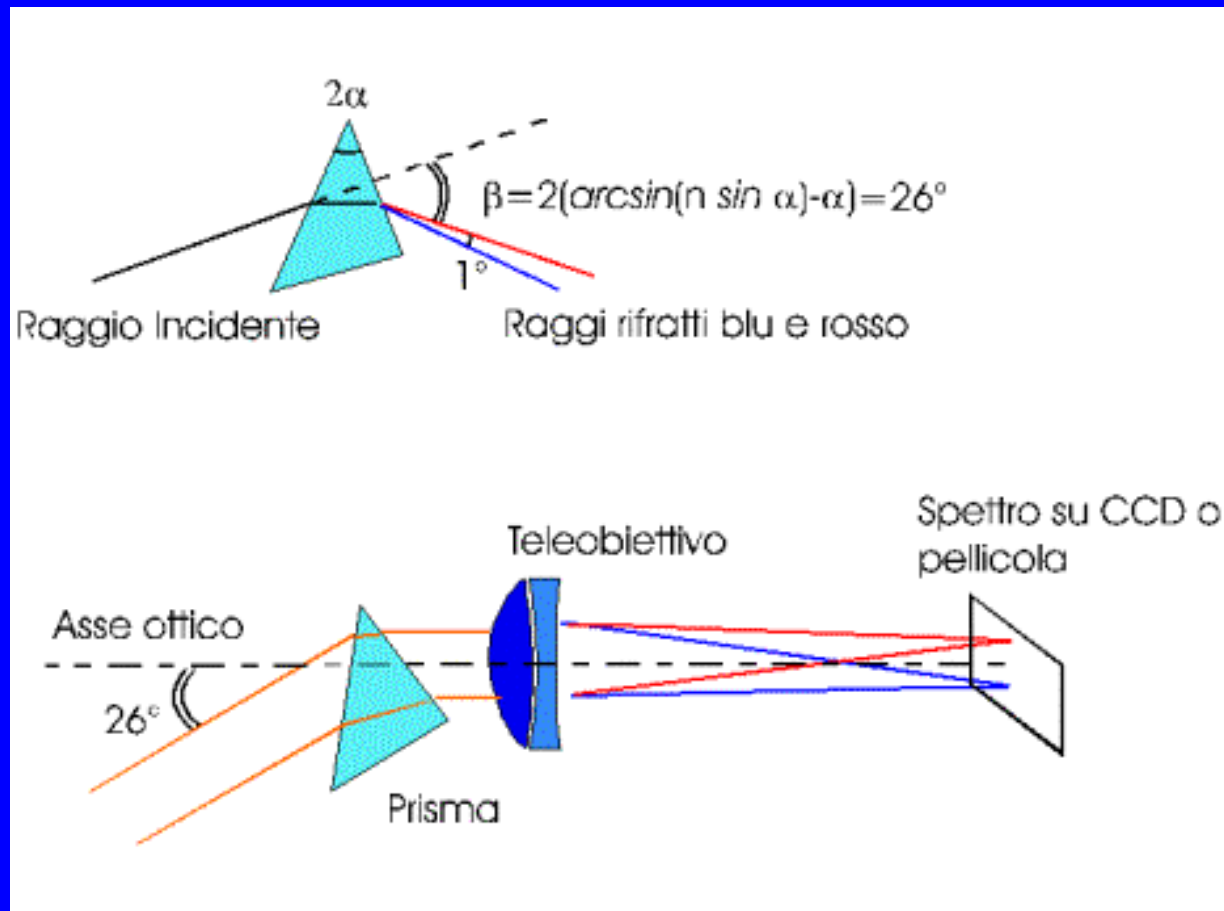


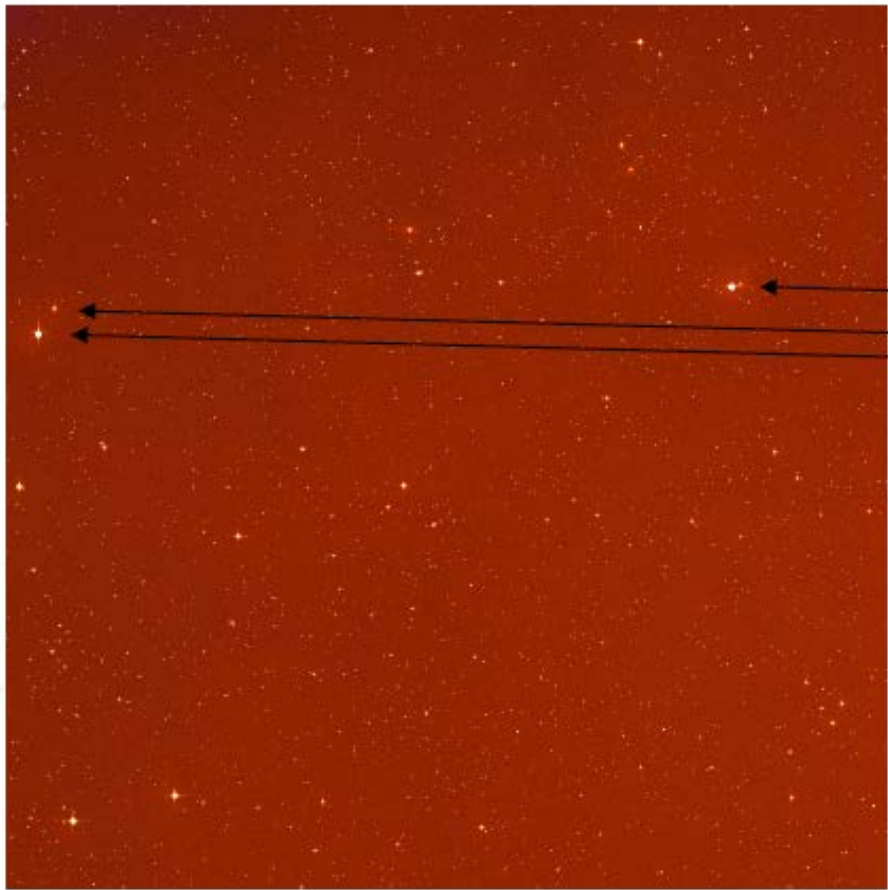
Sandage and coworkers (1986, 1987)

Carney and collaborators (1994)

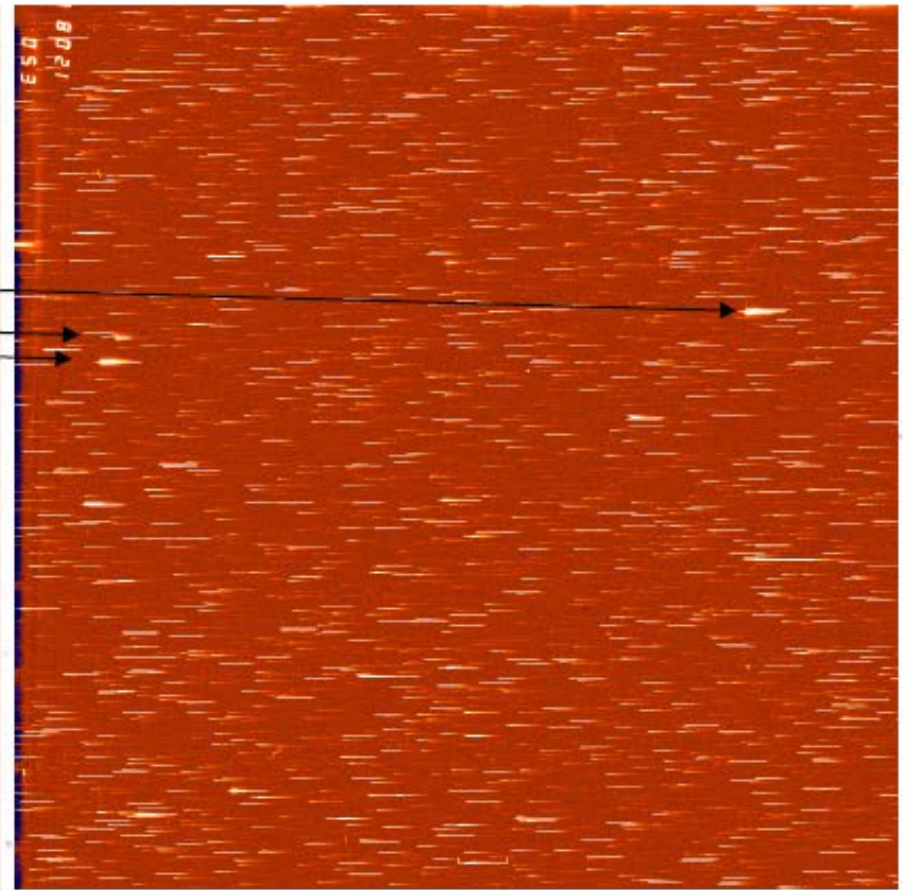
- In the published work, fewer than 10% of the stars in these catalogs have  $[\text{Fe}/\text{H}] < -2.0$ .
- Great majority of candidates selected on the basis of their large proper motions alone are expected to have  $[\text{Fe}/\text{H}] > -2.0$ .

### 3. Objective-Prism survey:





Direct image

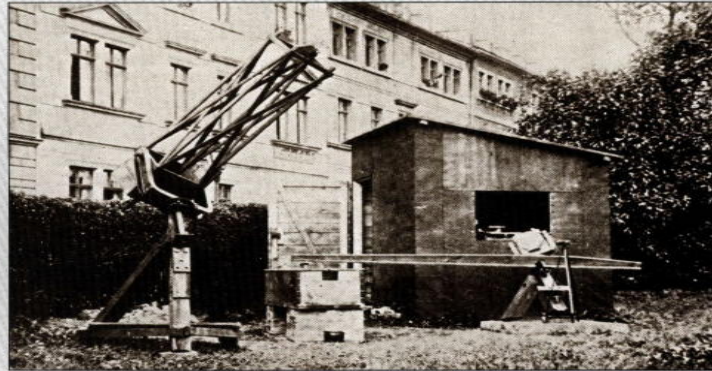


Objective-prism plate

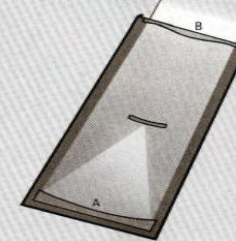
# Schmidt Telescope

BERNHARD SCHMIDT  
(1879–1935)

*Schmidt stammte aus Estland und schlug Linsen und Spiegel für Amateurastronomen. Später ging er an die Hamburger Sternwarte. Dort entwickelte er sein eigenes Teleskop, den »Schmidt-Spiegel«.*



*Oben: Bernhard Schmidts eigene »Sternwarte« in Mittweida in der Nähe von Jena, jetzt DDR, etwa 1920. Links steht ein Cassegrain-Reflektor mit Gabelmontierung, rechts ist ein Teil eines waagerechten Teleskops zu erkennen.*



*Der Schmidt-Spiegel verbindet, wie in der Schemazeichnung oben zu sehen ist, einen sphärischen Spiegel A mit einer Korrektionsplatte B. Die Korrektionsplatte berichtigt die sphärische Aberration des Spiegels über der Mitte des Spiegels. Die Form der Oberfläche der Korrektionsplatte ist in der Zeichnung stark übertrieben – die Abweichung von einer ebenen Fläche beträgt weniger als ein Zehntausendstel des Plattendurchmessers.*

*Links: Der 1,2-m-Schmidt-Spiegel auf Mount Palomar von 1948. Im Plattenhalter werden Platten von 34 cm Seitenlänge aufgenommen, die ein Himmelsgebiet von 6 Grad Durchmesser erfassen; ein einzelnes Photo enthält Bilder von bis zu einer Million Sternen.*

# Hamburger Sternwarte



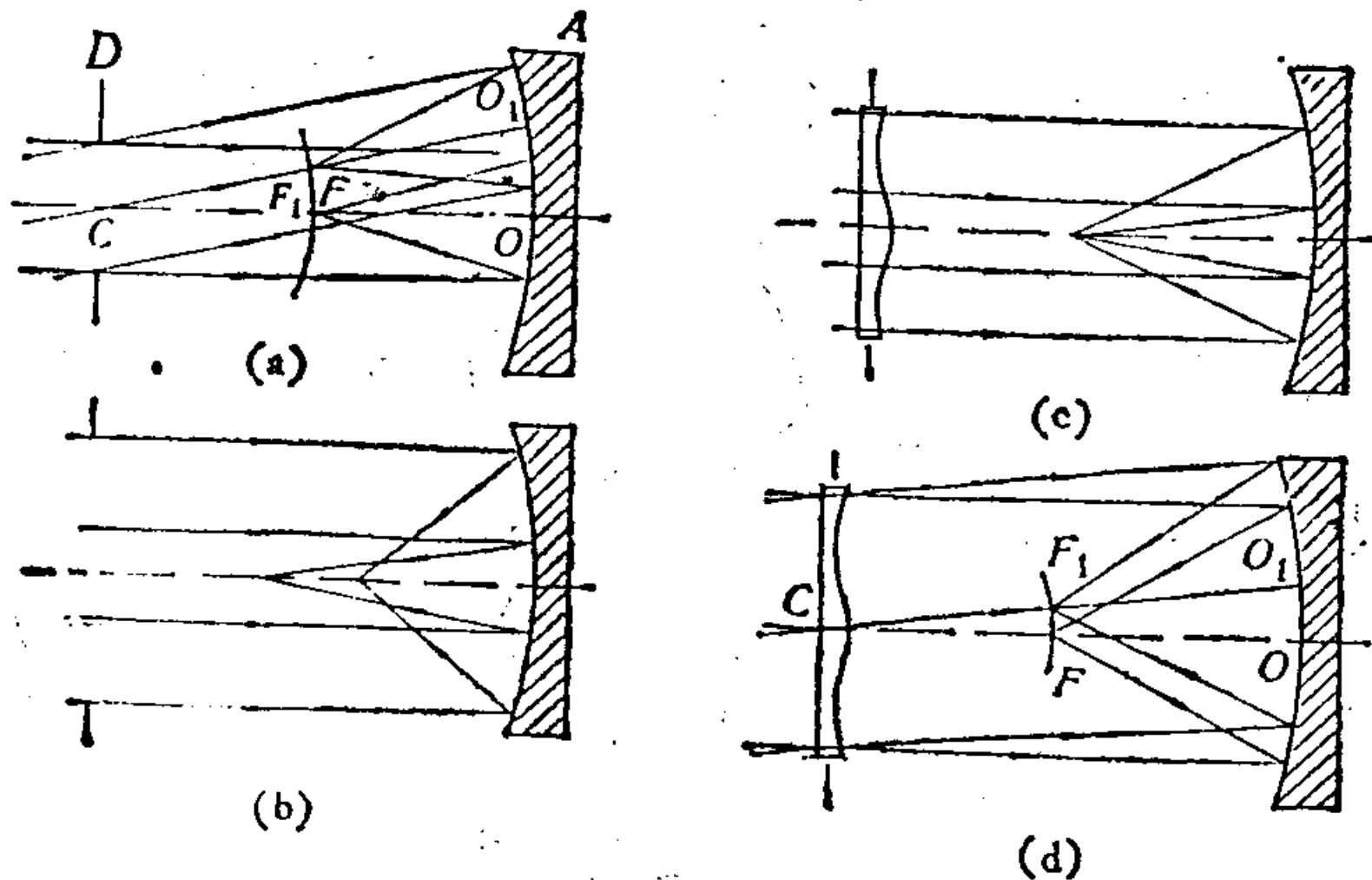


图 2.19 施密特折反射望远镜的成像

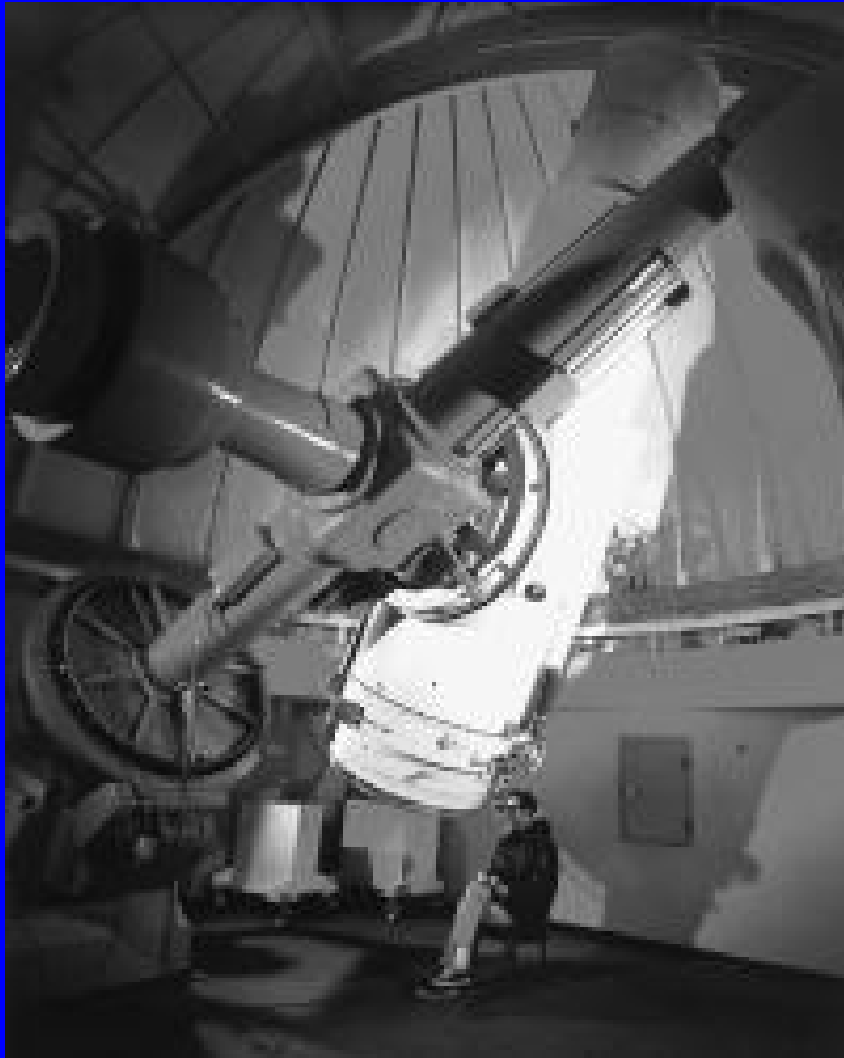
a. 消彗差、像散的原理； b. 未加校正板时存在球差； c. 加施密特校正板后消除了球差； d. 施密特折反射望远镜的光路图。

# Bond spectroscopic survey

- Bond (1980, 1981)
  - Nearly half a million objective prism spectra down to  $B=11.5$  mag. over 5000 square degrees
  - $B=10.5$  mag., covering half of the full sky.
- Only 3 stars with  $[\text{Fe}/\text{H}] \leq -3.0$

# The HK survey

- Beers, Preston, Sheckman (BPS survey):
- $B = 16$  mag.
- $[\text{Fe}/\text{H}] < -2.0$ :  $>1000$
- $[\text{Fe}/\text{H}] < -3.0$ :  $\sim 100$



## Southern Hemisphere:

- 0.6 m Curtis Schmidt Telescope at CTIO
- 4 degree objective prism
- $4100 \text{ deg}^2$

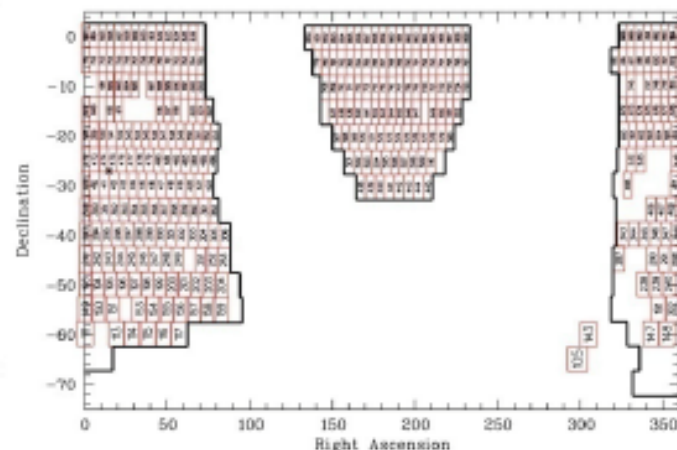


## Northern Hemisphere:

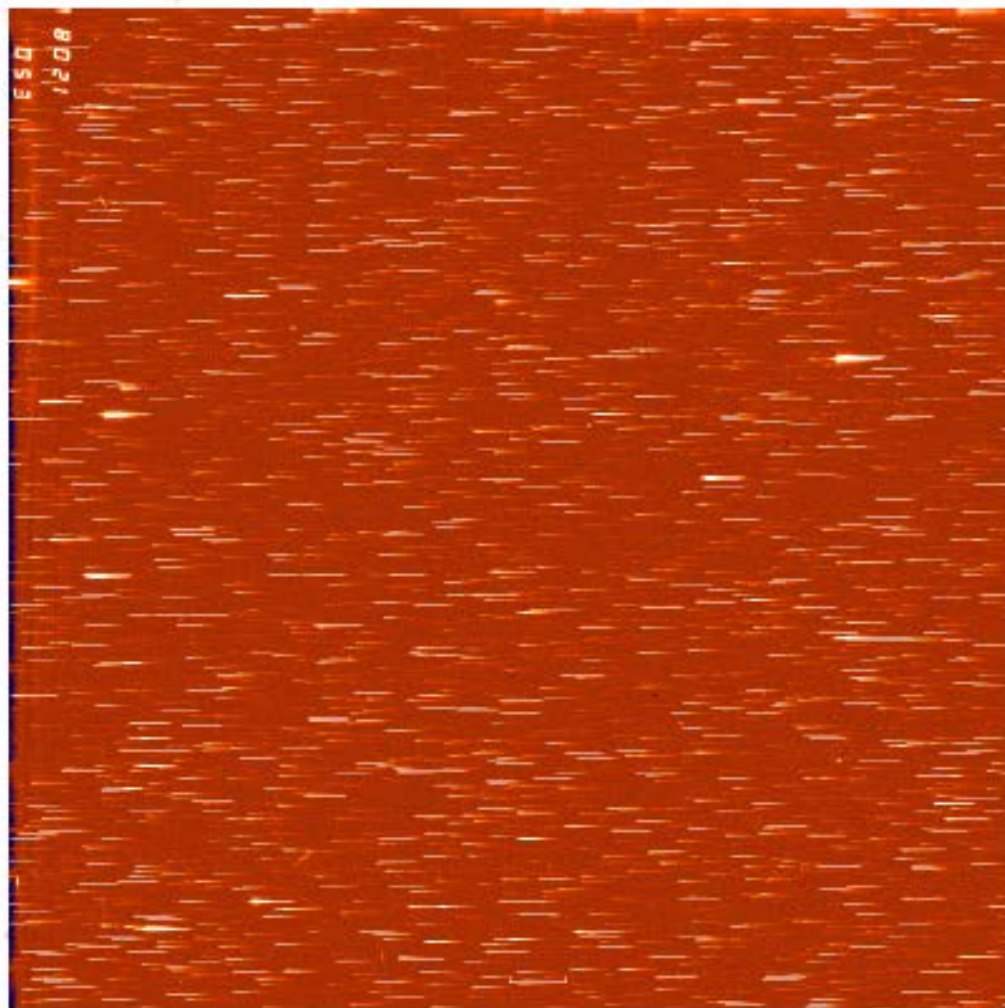
- 0.6 m Burrell Schmidt Telescope at KPNO
- 2800 deg<sup>2</sup>

# Hamburg/ESO survey (HES)

- Objective-prism survey covering half of the southern sky
- 379 plates,  $5^\circ \times 5^\circ$  each
- Plates were taken with the 1m ESO Schmidt telescope in the 1990ies, then digitized in Hamburg
- 12,397,333 digital spectra



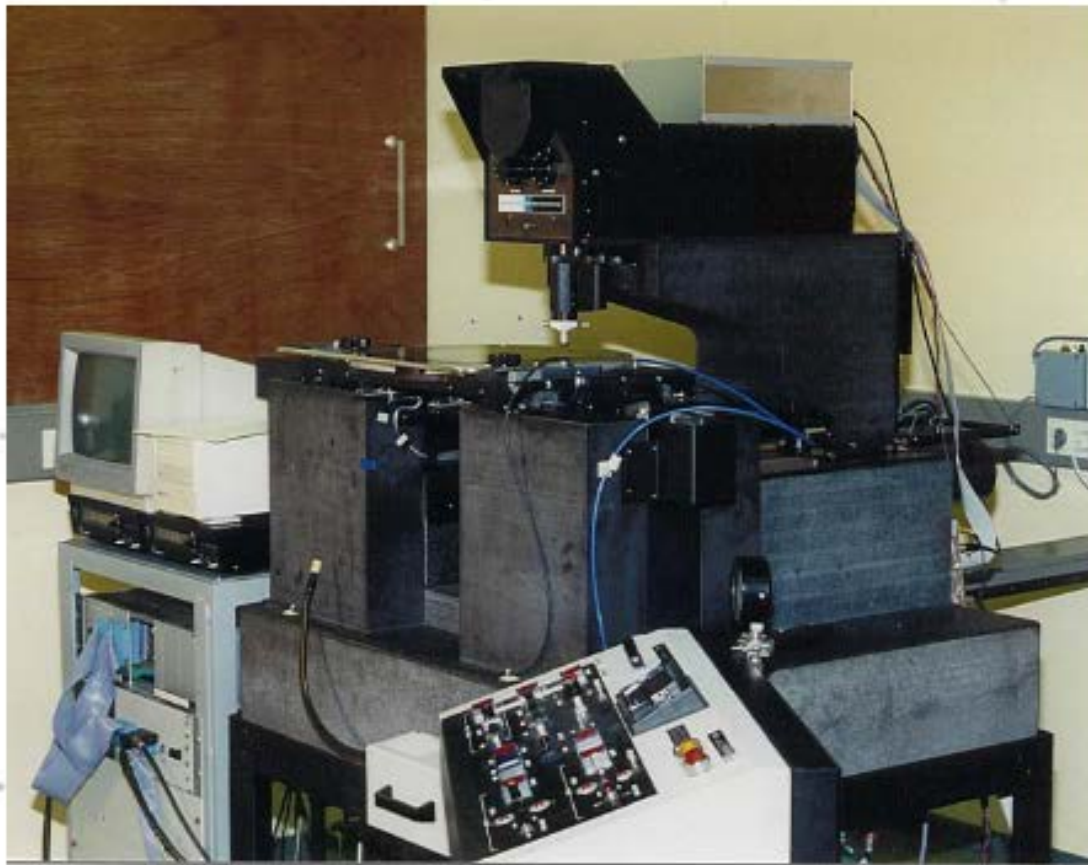
# Objective-prism plates



- Typical sky coverage:  $5^\circ \times 5^\circ$
- About 30,000 spectra per plate
- $\Delta\lambda \sim 10\text{\AA}$
- The interesting objects are very rare; e.g., one can find only 1–2 old, metal-poor stars on each plate

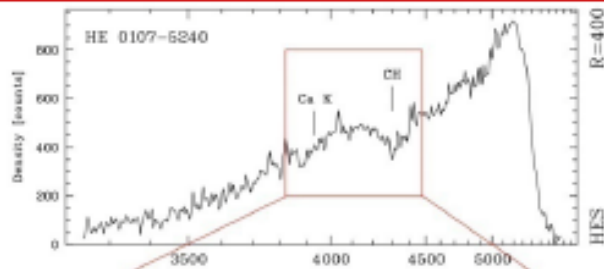
# Plate digitization

Digitization of objective-prism plates makes automated and quantitative selection possible



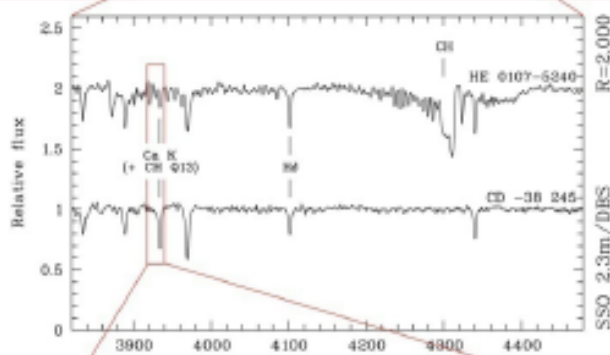
The Hamburg Observatory  
PDS plate scanner

# The main observational steps



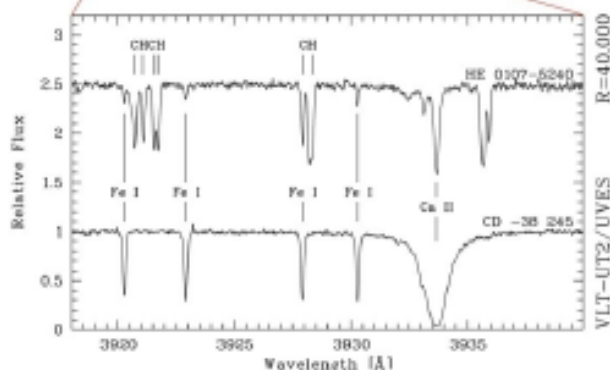
## 1. Candidate selection

Quantitative criteria based on Ca K line strength,  $B-V$  and  $J-K$  colours



## 2. Confirmation of candidates

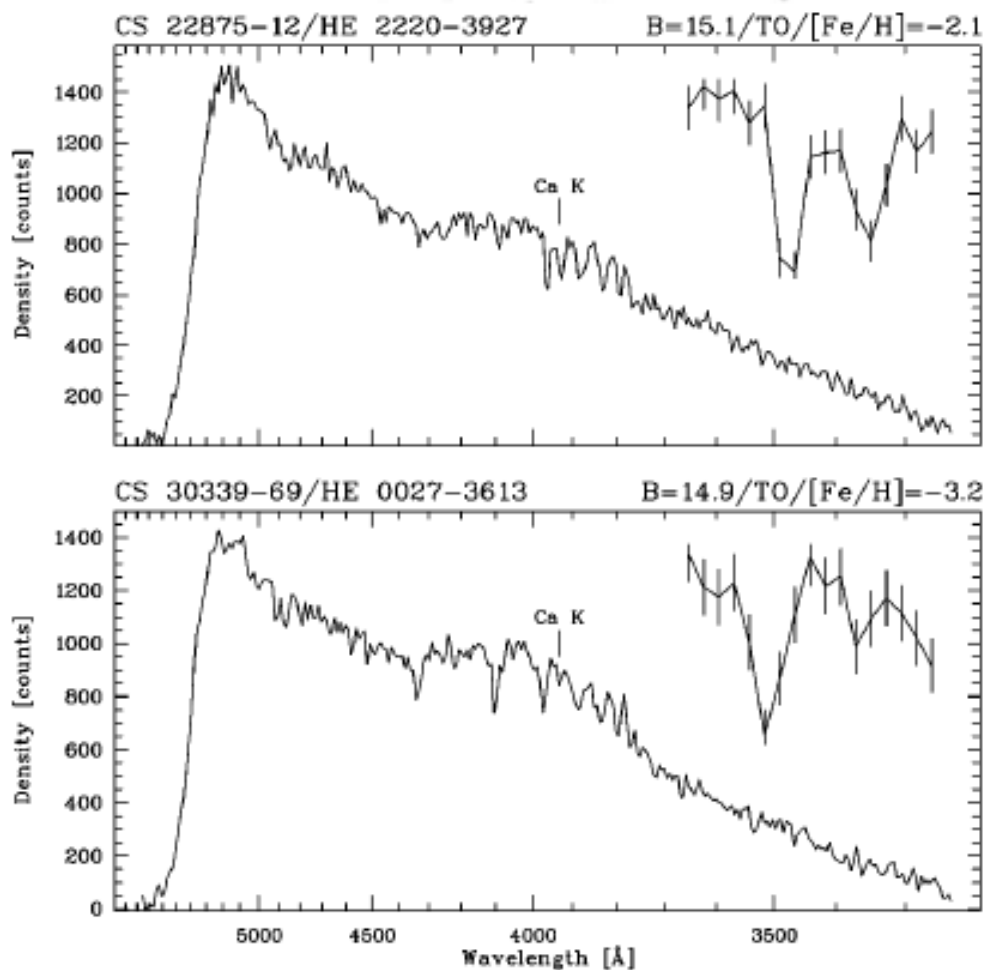
with moderate-resolution spectroscopy (i.e.,  $R \sim 2000$ )



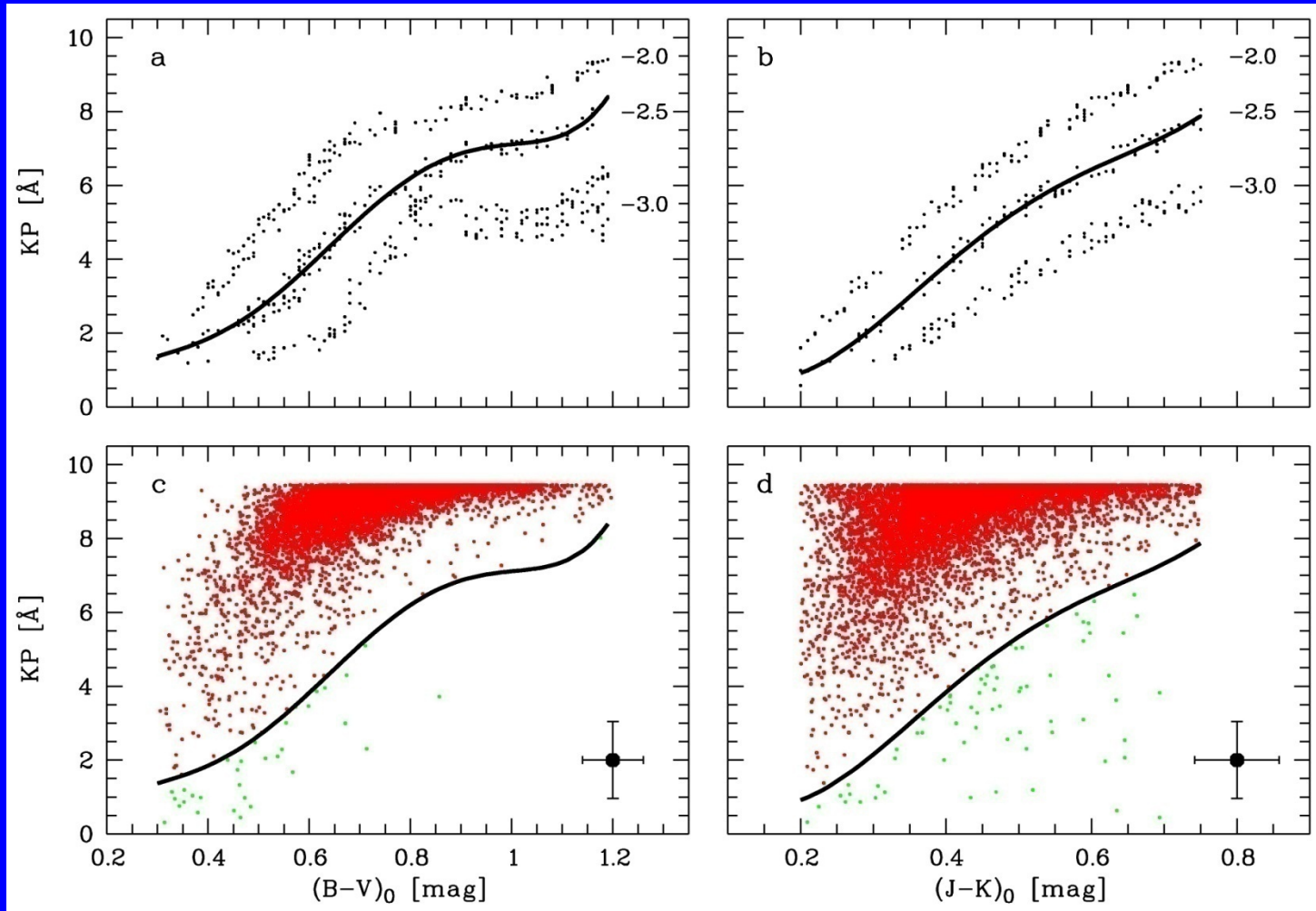
## 3. High-resolution spectroscopy

(i.e.,  $R > 40,000$ ) for determination of abundances of elements

# Selection of candidate metal-poor stars

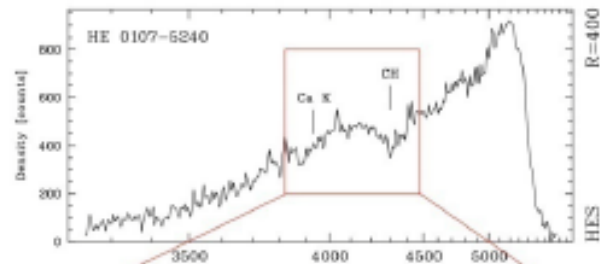


# Selection of candidate metal-poor stars



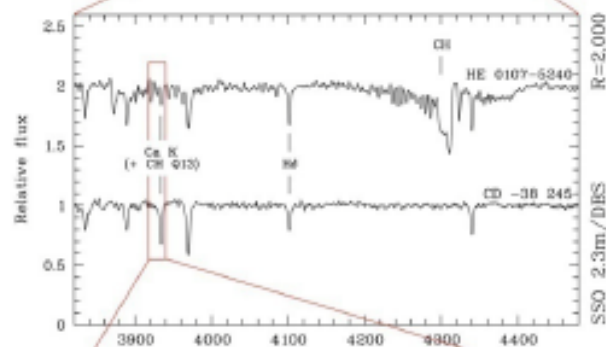
Christlieb et al. (2008)

# The main observational steps

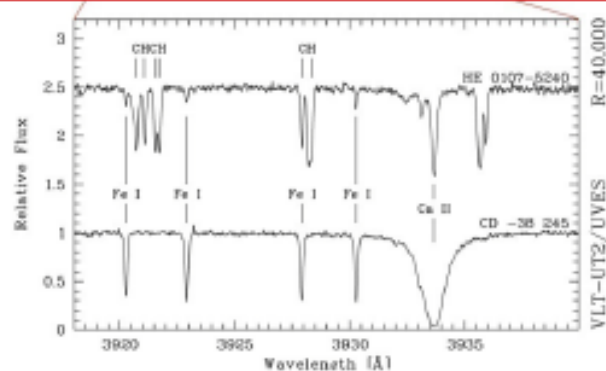


## 1. Candidate selection

Quantitative criteria based on Ca K line strength,  $B-V$  and  $J-K$  colours

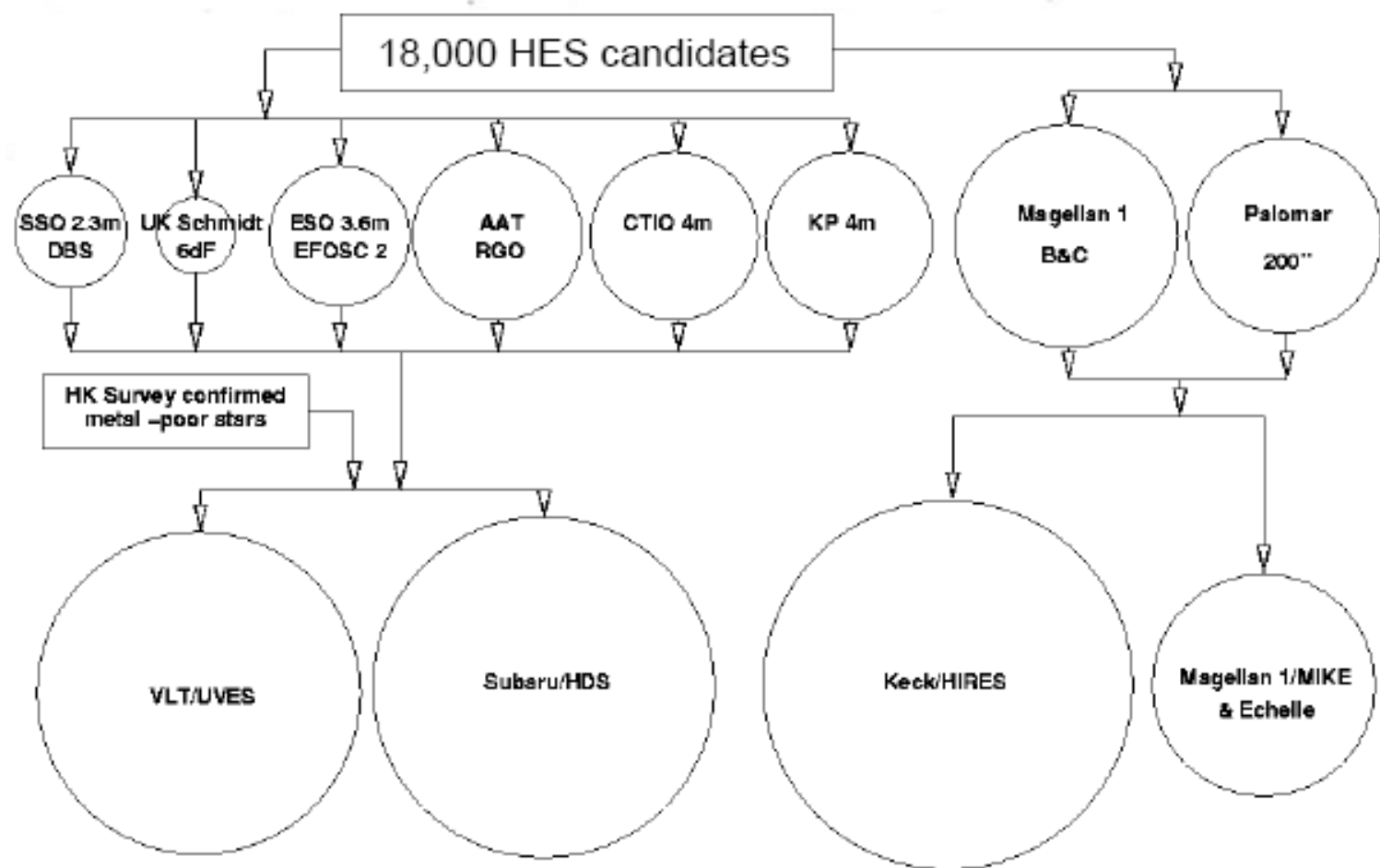


## 2. Confirmation of candidates with moderate-resolution spectroscopy (i.e., $R = 2000$ )

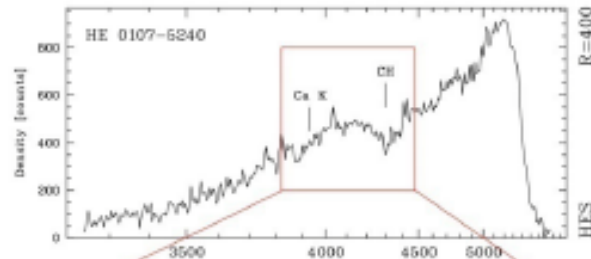


## 3. High-resolution spectroscopy (i.e., $R > 40,000$ ) for determination of abundances of elements

# HES metal-poor star flow chart

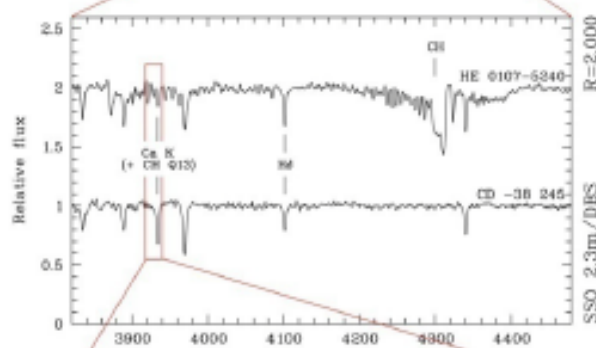


# The main observational steps



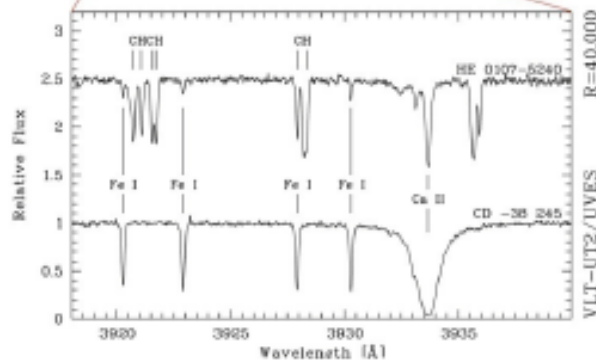
## 1. Candidate selection

Quantitative criteria based on Ca K line strength,  $B-V$  and  $J-K$  colours



## 2. Confirmation of candidates

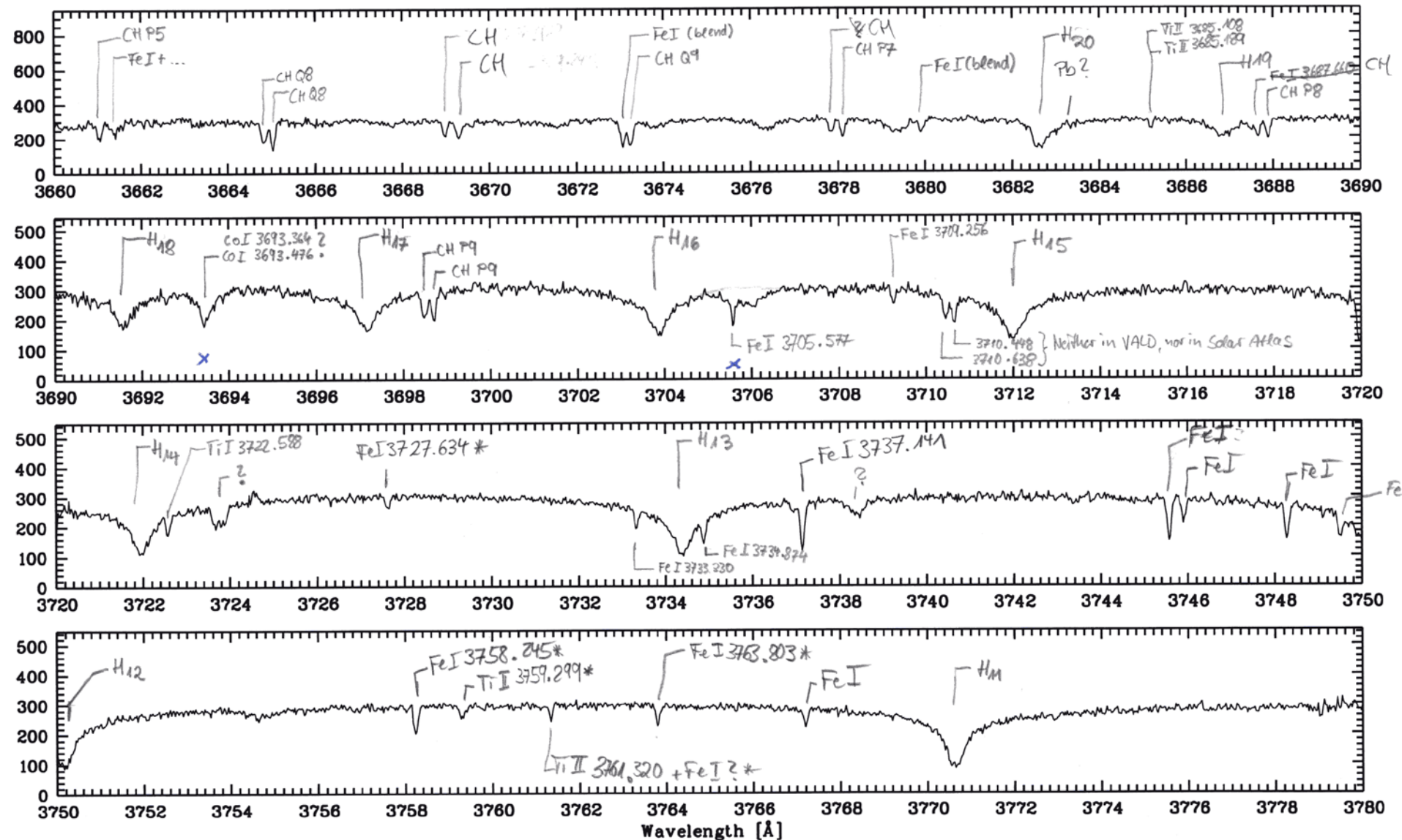
with moderate-resolution spectroscopy (i.e.,  $R = 2000$ )



## 3. High-resolution spectroscopy

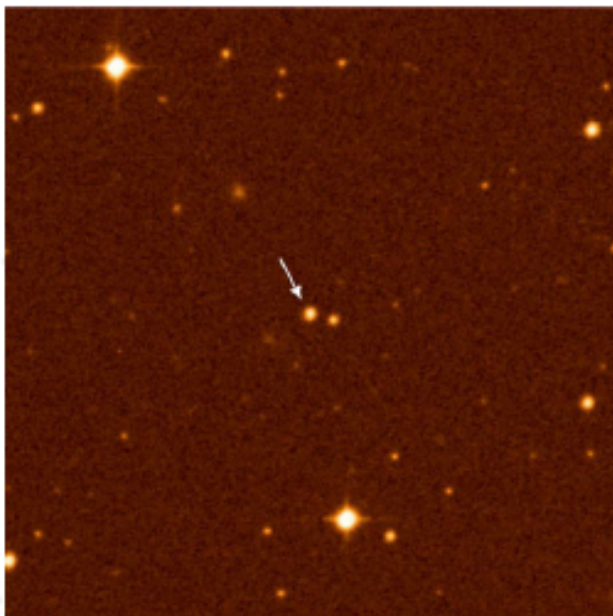
(i.e.,  $R > 40,000$ ) for determination of abundances of elements

# High-resolution spectroscopy



- 329 HES fields
- 8225 degree<sup>2</sup>
- $10 < B < 17.5$
- candidate metal-poor stars: 10000
  
- Follow-up medium resolution observation:
  - 4000 metal-poor stars candidates
  - 200 with  $[\text{Fe}/\text{H}] < -3.0$

HE 0107-5240  
[Fe/H] = -5.3



The Very Metal-Deficient Star HE 0107-5240

ESO PR Photo 25a/02 (30 October 2002)

© European Southern Observatory

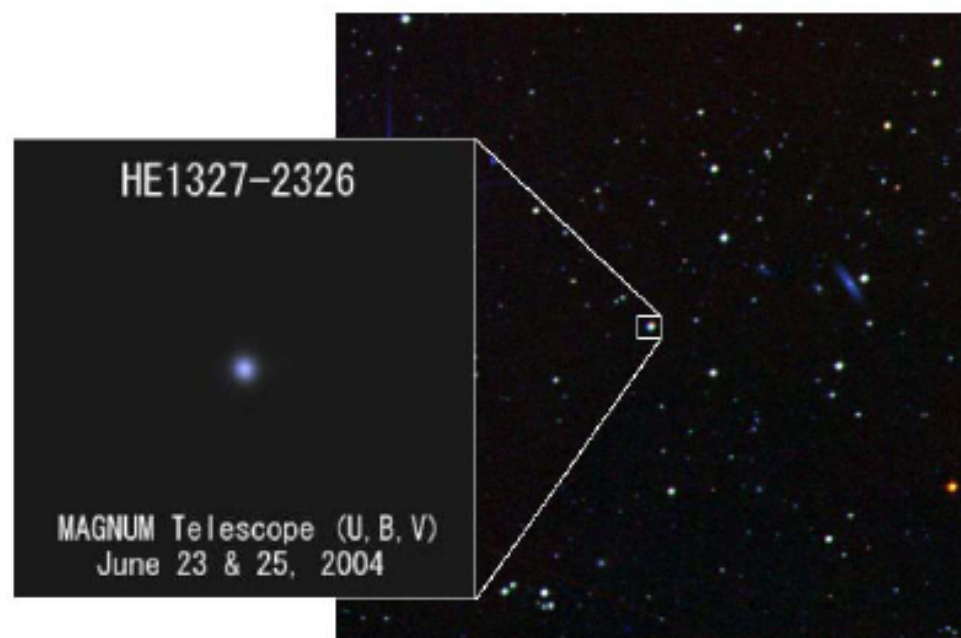


Christlieb et al. (2002), Nature 419, 904  
Christlieb et al. (2004), ApJ 603, 708  
Bessell et al. (2004), ApJ 612, L61  
Christlieb et al. (2008), in preparation

# The most heavy-element deficient stars known

HE 1327-2326  
[Fe/H] = -5.4

Frebel et al. (2005), Nature 434, 871  
Frebel et al. (2006), ApJ 638, L17  
Aoki et al. (2006), ApJ 639, 897



DSS Image (R,G,B)

# Some basic facts

	HE 0107–5240	HE 1327–2326
$T_{\text{eff}}$	5100 K	6180 K
$\log g$	2.2 dex	3.7 dex
$[\text{Fe I}/\text{H}]_{\text{NLTE}}$	–5.3 dex	–5.4 dex
$\mu$	?	0.0733 arcsec/yr
$B$	15.86 mag	14.016 mag
$E(B-V)$	0.013 mag	0.060–0.096 mag
$(B-V)_0$	0.68 mag	0.40 mag
$(V-K)_0$	1.90 mag	1.32 mag



# SCIENCE NEWS

THE WEEKLY NEWSMAGAZINE OF SCIENCE

NOVEMBER 2, 2002 PAGES 273-288 VOL. 162, NO. 18

ancient inland ocean  
herbicide alters frog sex organs  
a star from the beginning?  
new painkiller headache

www.sciencenews.org

## Arm an Eisen

Alter Stern stützt kosmologische Theorie

Der Urknall hat fast ausschließlich Wasserstoff und Helium hervorgebracht, aber keinen Kohlenstoff und kein Eisen. Diese schweren Elemente mussten die ersten Sterne einer Grundthese der Kosmologie zufolge quasi erbrüten und nach ihrem Tod als Explosionsreste einer Supernova ins Weltall hinausblasen. Allerdings hatte diese These bislang einen Makel: Nirgendwo im All konnten Astronomen einen Stern jener ersten Generation finden, der keine schweren Elemente enthält. Diesem Ziel sehr nahe gekommen ist jetzt ein Team um Norbert Christlieb von der Hamburger Sternwarte und Mike Bessel vom Mount-Stromlo-Observatorium in Australien. Die Forscher haben einen schwachen Stern entdeckt, der nicht einmal ein Hunderttausendstel des Eisens enthält, das in der Sonne steckt (*Nature*, Bd. 419, S. 904, 2002). Mit einem geschätzten Alter von zwölf Milliarden Jahren gehört er zudem zu den Greisen der Milchstraße. Bislang hatten Theoretiker vermutet, dass im frühen Universum fast ausschließlich sehr massereiche Sterne entstanden sind; sie wären nämlich bis heute längst erloschen. Der jetzt entdeckte Himmelskörper besitzt aber etwas weniger Masse als die Sonne. Damit wächst die Chance, auch noch Sterne der allerersten Generation zu finden. **TR**

SÜDDEUTSCHE ZEITUNG, 5.11.2002

## Iron-Poor Star

### Closing in on the birth of the first stars

For decades, astronomers have been searching for stars born soon after the Big Bang, around the time the Milky Way began forming. Researchers now report that they've found one of these ancient stars.

According to a widely accepted theory, the Big Bang forged nearly all of the hydrogen and helium in the universe but only trace amounts of a few other heavier elements. In time, as star formation

## Gammal stjärna extremt lätt

Astronomer i Uppsala har hittat en av universums äldsta stjärnor. Den kan ge unik information om tillståndet strax efter Big Bang.

– Kemiskt sett är det här det närmaste vi har kommit Big Bang, säger Bengt Gustafsson, som är professor i astrofysik vid Uppsala universitet.

Han är en av författarna till rapporten om den äldsta stjärnan, som publiceras i dagens nummer av tidskriften *Nature*. Huvudarbetet har gjorts av den tyske astronomen Norbert Christlieb, som vid tiden för upptäckten var gästforskare i Uppsala.

Astronomer mäter stjärnors ålder genom att studera deras innehåll. Ju tyngre grundämnen de innehåller, desto yngre är de. Det betyder också att de är lättare.

DN, 31.10.02

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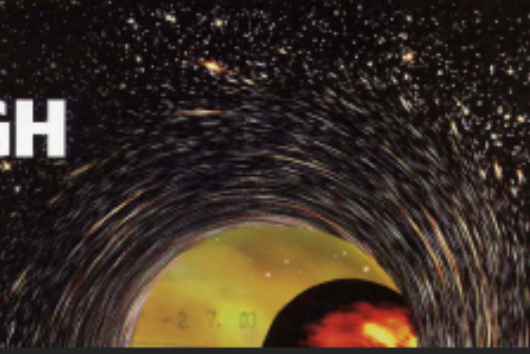
# NewScientist

The global science and technology weekly | 28 June 2003

THE BEST JOBS IN SCIENCE

## A VIEW THROUGH TIME

Our first glimpse of the earliest stars



## Rätselhaftige Sterne

Boten aus der Frühzeit des Kosmos arm an Metallen

Als das Universum mit einem Urknall entstand, haben sich nur Wasserstoff und Helium sowie Spuren von Lithium gebildet. Alle schwereren Elemente, von den Astronomen insgesamt als Metalle bezeichnet,

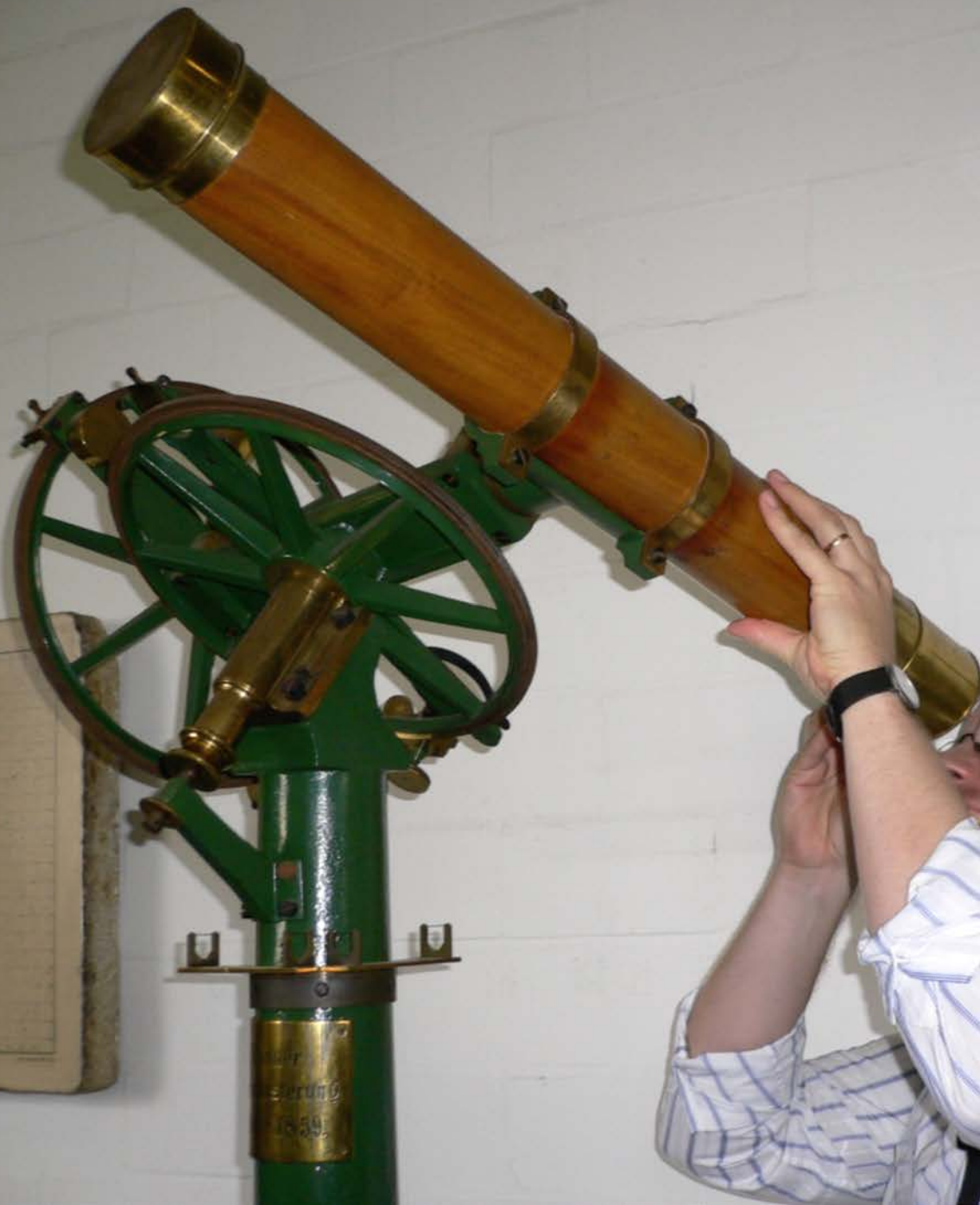
zufolge durfte es so „leichtgewichtige“ metallarme Sterne in der Anfangszeit des Universums gar nicht gegeben haben. Jün Studien lassen vermuten, daß sich aus interstellarem Material, das keine Metalle enthält, ursprünglich mindestens zweihundert-

FAZ, 30.4.03

w

**GUINNESS  
WORLD RECORDS  
RECORDS**





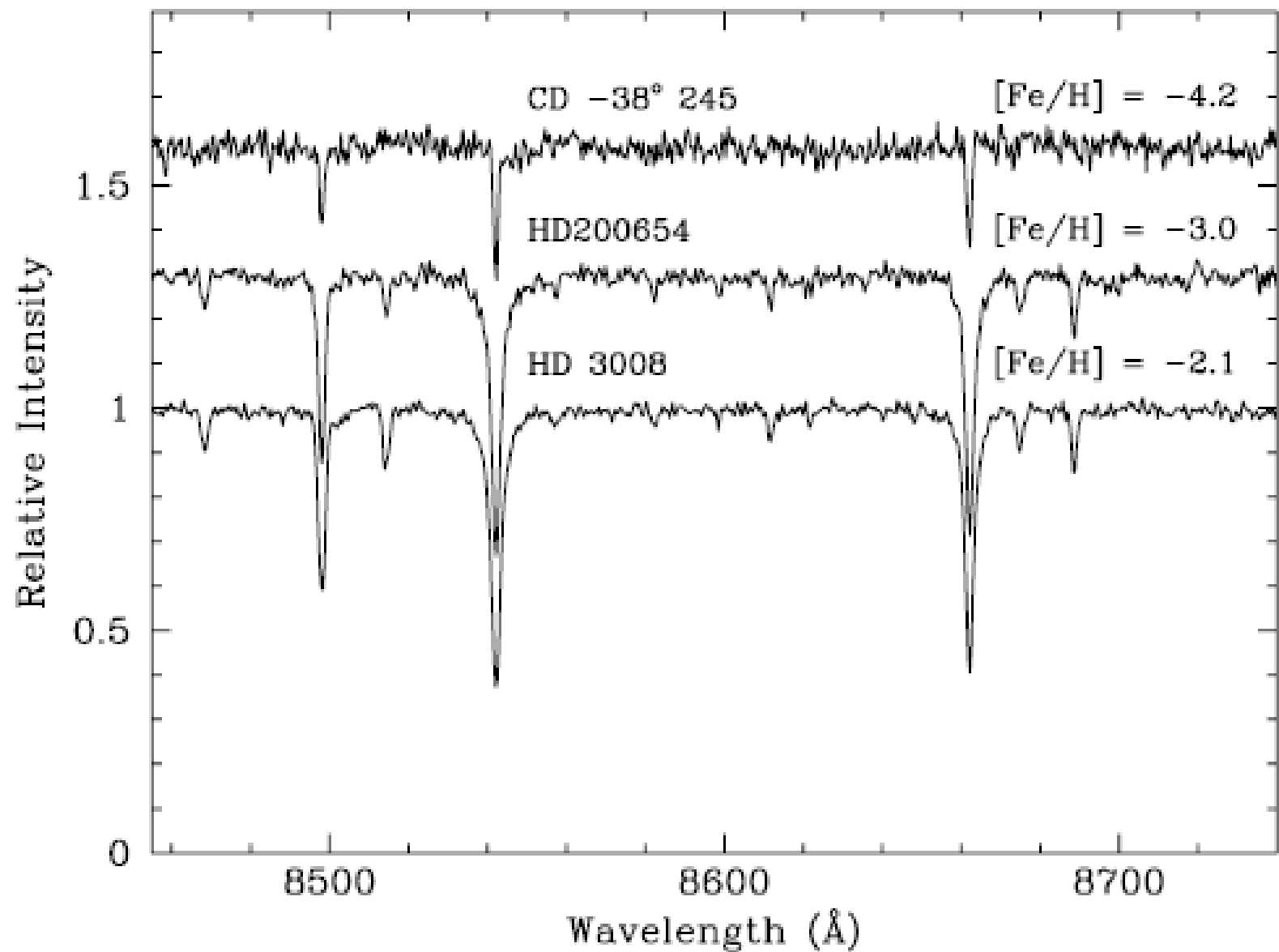
## 4. Multi-fiber spectroscopic survey

- RAVE
  - SDSS
  - LAMOST
- 
- Much **larger** and **deeper** surveys will provide statistically **complete sample** of very metal-poor stars.

# RAVE:

Steinmetz et al. 2006, Zwitter et al. 2008

- 1.2m Schmidt telescope at AAO
- FOV:  $6^\circ$
- Fiber: 150
- $R \sim 7500$
- Wavelength coverage:  $8410 - 8795 \text{ \AA}$
- Exposure time:  $\sim 50$  min
- Limit magnitude:  $9 < I < 12$
- Sky coverage:  $\sim 12200$  square degree



# Fulbright et al. (2010)

- Identified 631 stars with  $[\text{Fe}/\text{H}] \leq -2$  from a RAVE database containing  $\sim 200000$  stars.
- 3 stars with  $[\text{Fe}/\text{H}] \leq -4$ 
  - C22448-172429:  $[\text{Fe}/\text{H}] = -4.0$
  - CD-38 245:  $[\text{Fe}/\text{H}] = -4.2$
  - ?(at the limit of S/N ratio):  $[\text{Fe}/\text{H}] = -4.0$

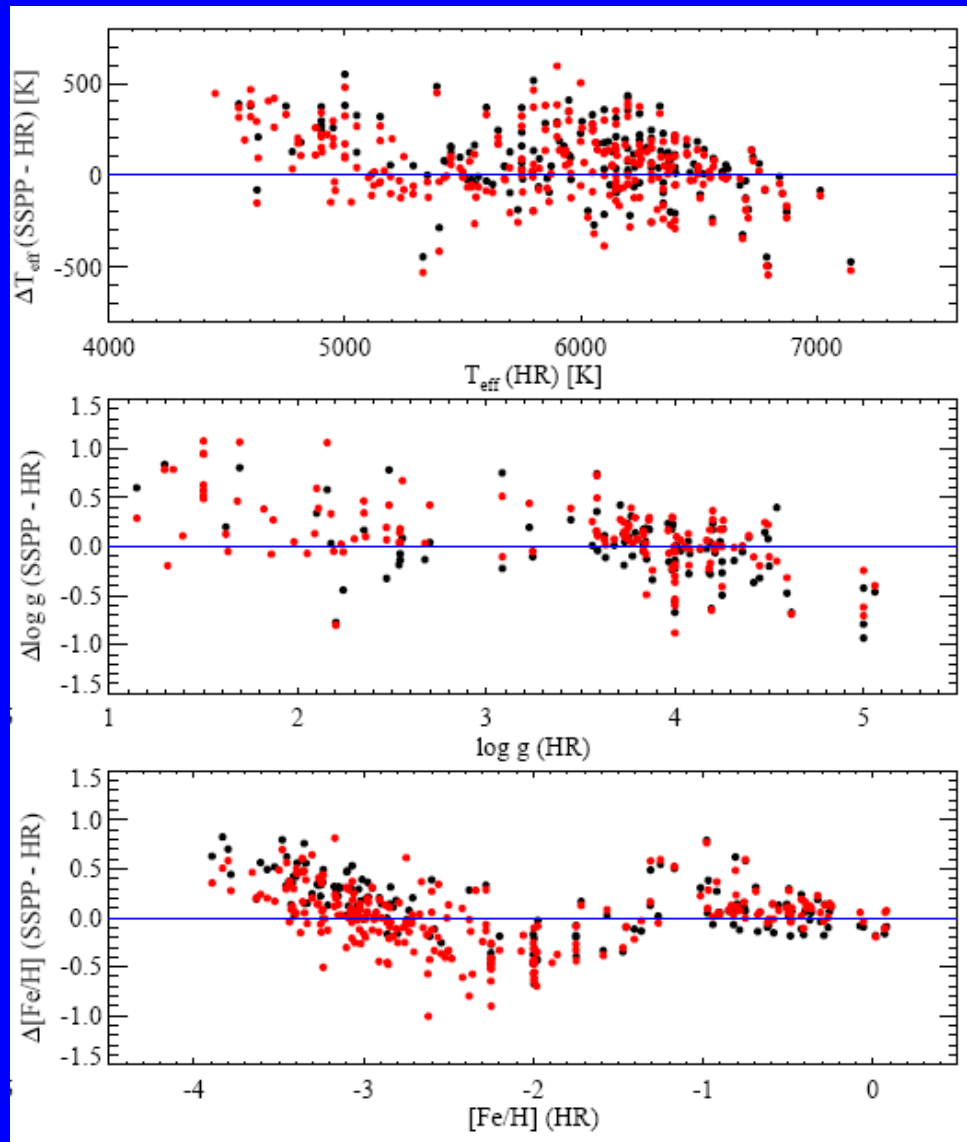
# SDSS DR7

- SSPP ( $4500 \text{ K} \leq T_{\text{eff}} \leq 7500 \text{ K}$ ):
  - $\sigma(T_{\text{eff}}) = 157 \text{ K}$
  - $\sigma(\log g) = 0.29$
  - $\sigma([\text{Fe}/\text{H}]) = 0.24$
- 460000 star
  - $[\text{Fe}/\text{H}] \leq -2$ : ~30000
  - $[\text{Fe}/\text{H}] \leq -3$ : ~700
  - $[\text{Fe}/\text{H}] \leq -4$ : 0 !



- There exists a **degeneracy** between the stellar parameters and metallicity.
- The strengths of the Ca Triplet lines can be **equal** for both a **lower-metallicity cooler giant** and a **higher-metallicity hotter turn-off star**.
- A **temperature** difference of **100 K** corresponds to a **metallicity** difference of about **0.1 dex**.

# SSPP pre-DR8 (Smolinski et al. 2010)



# Search for VMP star candidates in SDSS

*Xu S.Y. et al. (2011)*

- Select stars with  $[\text{Fe}/\text{H}] < -3.5$ ,  $S/N > 20$  from SDSS DR8 .
- 45 stars are re-analysed.
  - Modified SSPP
  - EW analysis

# Results

No.    Teff    log g    DR8    [Fe/H]    HR

---

1.    5775    3.24    -3.8    -4.10    -4.99

2.    6110    3.61    -3.7    -3.80    -4.09

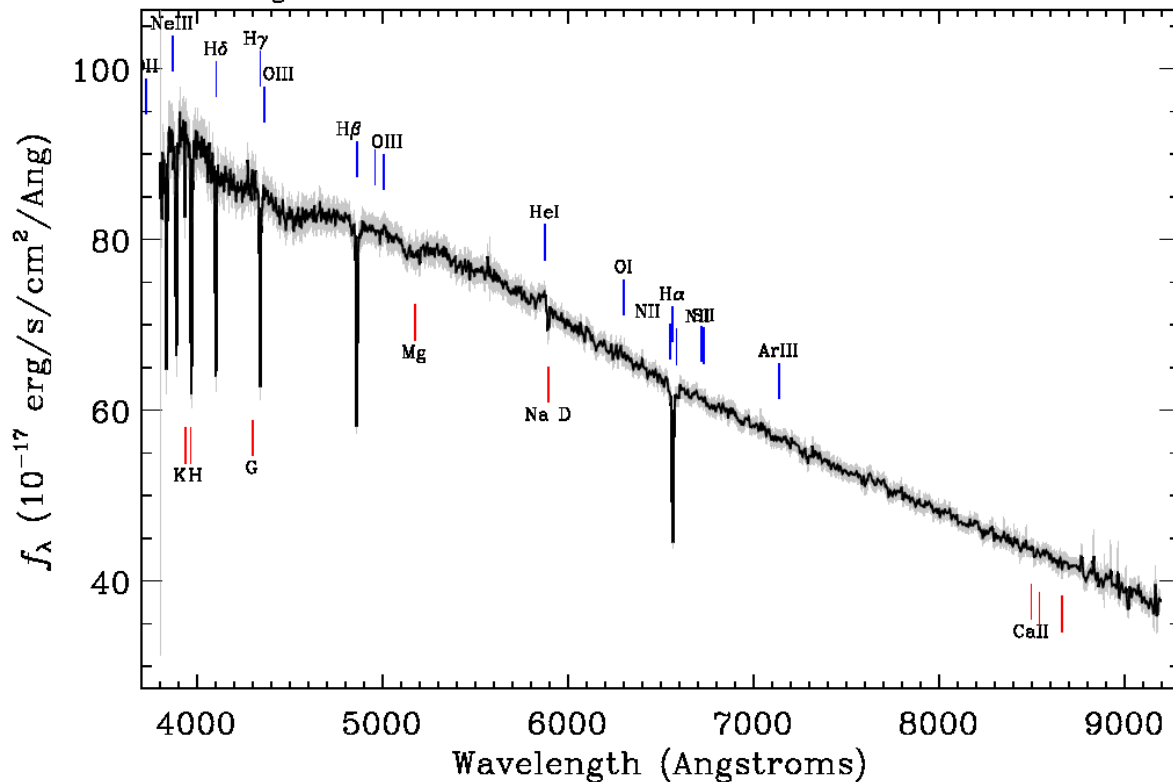
3.    6138    3.59    -3.5    -3.90    -3.57  $\alpha$ -poor

4.    5908    3.48    -3.6    -3.90    -3.96

5.    4462    1.59    -3.7    -3.90

6.    4464    0.86    -3.5    -4.02

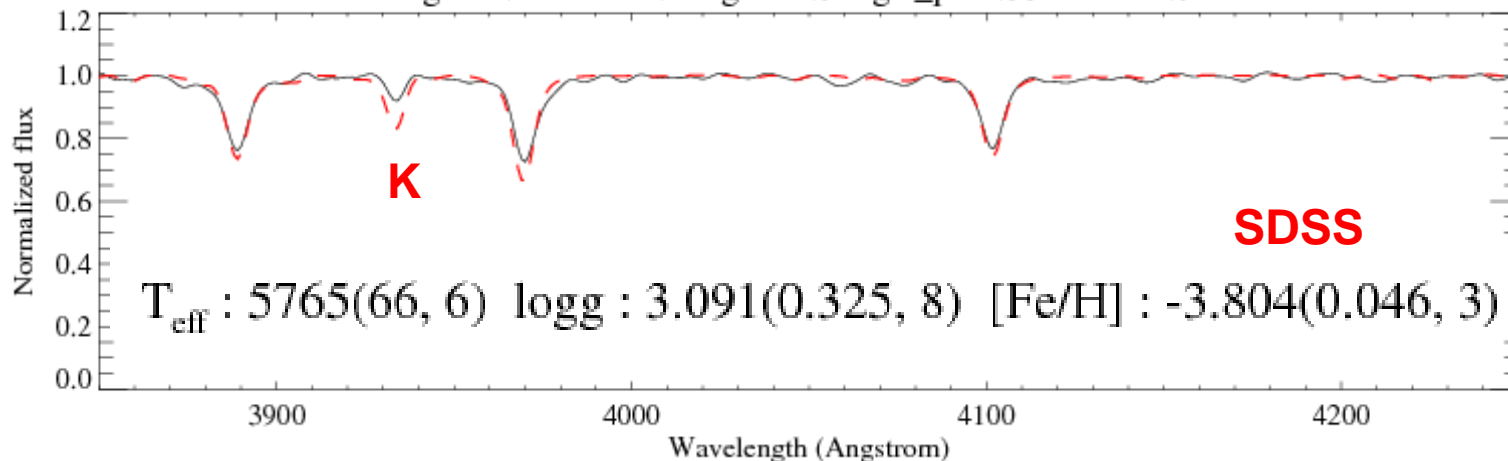
Survey: *segue1* Program: *segpointed Target: F\_STAR*  
RA=157.31313, Dec=17.49110, Plate=2853, Fiber=113, MJD=54440  
cz=-35+/-4 km/s Class=STAR B6  
No warnings.



SDSS  
J102915+172927

[Fe/H] ~ -4.50

g : 16.82 V : 16.61 g-r : 0.36 g-r\_p : 0.33 B-V : 0.52

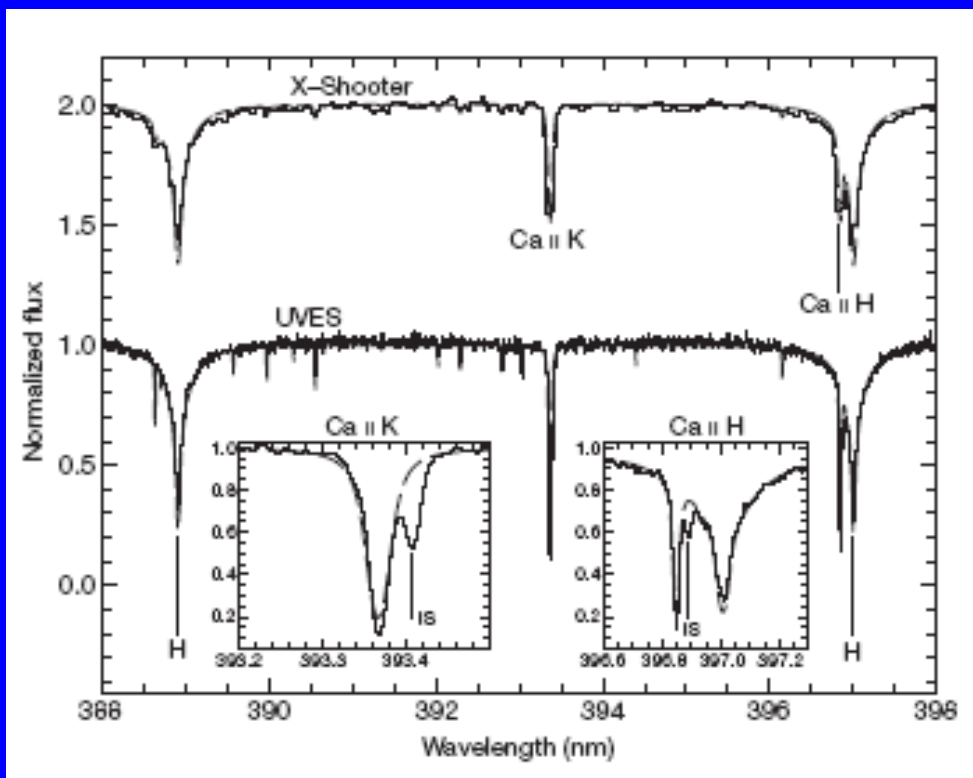


## An extremely primitive star in the Galactic halo

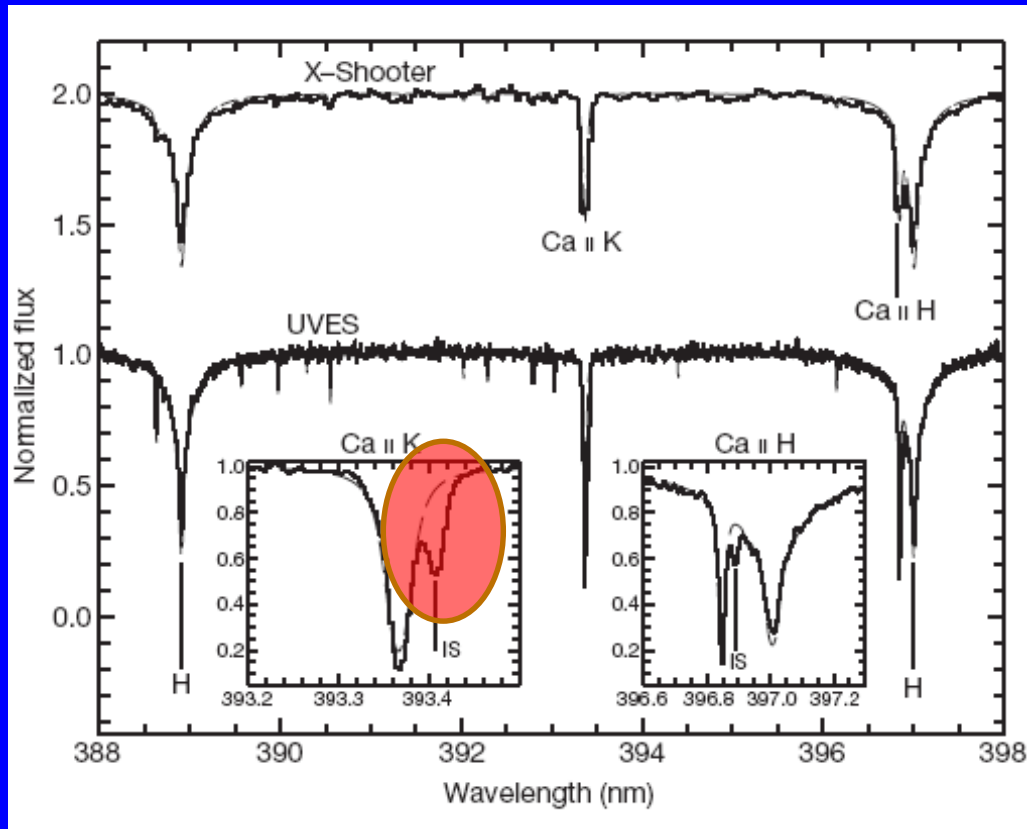
Elisabetta Caffau<sup>1,2</sup>, Piercarlo Bonifacio<sup>2</sup>, Patrick François<sup>2,3</sup>, Luca Sbordone<sup>1,2,4</sup>, Lorenzo Monaco<sup>5</sup>, Monique Spite<sup>2</sup>, François Spite<sup>2</sup>, Hans-G. Ludwig<sup>1,2</sup>, Roger Cayrel<sup>2</sup>, Simone Zaggia<sup>6</sup>, François Hammer<sup>2</sup>, Sofia Randich<sup>7</sup>, Paolo Molaro<sup>8</sup> & Vanessa Hill<sup>9</sup>



### SDSS J102915+172927



- VLT
  - X-shooter
  - UVES
- $T_{\text{eff}}=5811$  K
- $\text{Log } g=4.0$
- $M_t=1.5$  km/s
- $[\text{Fe}/\text{H}]_{1\text{D}}=-4.73\pm 0.13$
- $[\text{Fe}/\text{H}]_{3\text{D}}=-4.99\pm 0.12$



- SDSS spectra:  $[Fe/H] \sim -4.5$
  - VLT spectra:  $[Fe/H] = -4.73$
- Absorption due to interstellar gas

- SDSS J102915+172927 is **most metal-poor** star, although **not most iron-poor** of all stars yet studied.

**Table 1 | Abundances in SDSS J102915+172927**

Element	$A(X)$ , 3D	$[X/H]$ , 3D	$[X/Fe]$ , 3D	$[X/H]$ , 1D	Number of lines	$A(X)_{\odot}$
C	$\leq 4.2$	$\leq -4.3$	$\leq +0.7$	$\leq -3.8$	G band	8.50
N	$\leq 3.1$	$\leq -4.8$	$\leq +0.2$	$\leq -4.1$	NH band	7.86
MgI	2.95	$-4.59 \pm 0.10$	+0.40	$-4.68 \pm 0.08$	4	7.54
SiI	3.25	$-4.27 \pm 0.10$	+0.72	$-4.27 \pm 0.10$	1	7.52
CaI	1.53	$-4.80 \pm 0.10$	+0.19	$-4.72 \pm 0.10$	1	6.33
CaII	1.48	$-4.85 \pm 0.11$	+0.14	$-4.71 \pm 0.11$	3	6.33
TiII	0.14	$-4.76 \pm 0.11$	+0.23	$-4.75 \pm 0.11$	6	4.90
FeI	2.53	$-4.99 \pm 0.12$	+0.00	$-4.73 \pm 0.13$	44	7.52
NiI	1.35	$-4.88 \pm 0.11$	+0.11	$-4.55 \pm 0.14$	10	6.23
SrII	$\leq -2.28$	$\leq -5.2$	$\leq -0.21$	$\leq -5.1$	1	2.92

- HE0107-5240

	1D	3D	$\sigma$
[C/Fe]	+3.9	+2.9	0.2
$^{12}\text{C}/^{13}\text{C}$	60	60	10
[N/Fe]	+2.7	+1.7	0.2
[O/Fe]	+2.6	+1.9	0.2
[Mg/Fe]	+0.6	+0.5	0.2
[Sc/Fe]	+0.2	+0.1	0.2
[FeI/H] <sub>LTE</sub>	-5.4	-5.6	0.1
[FeII/H]	-5.7	-5.7	0.2
[Co/Fe]	+0.7	+0.5	0.2
[Ni/Fe]	+0.1	-0.2	0.1

# HE1327-2326

Species	[X/H] <sub>3D</sub>	[X/Fe] <sub>3D</sub>
C (CH).....	-2.18	3.78
N (NH).....	-1.68	4.28
O (OH).....	-2.54	3.42
Na I.....	-3.23	2.73
Mg I.....	-3.99	1.97
Al I.....	-4.50	1.46
Ca I.....	-5.52	0.44
Ca II.....	-5.05	0.91
Ti II.....	-5.05	0.91
Fe I.....	-5.96	...
Ni I.....	-5.78	0.18
Sr II.....	-4.79	1.17

- SDSS J102915+172927 has a mass smaller than that of the Sun and is probably more than **13 Gyr old**.
- A widely accepted theory predicts that stars like this, with low mass and extremely low quantities of metals, shouldn't exist because the clouds of material from which they formed could never have condensed.
  - **The star that should not exist!**

# Science

AAAS

## Breakthrough of the Year, 2011

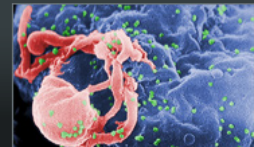
The year 2011 saw scientific research that stretched from the farthest reaches of the universe to the deepest mysteries of the cell. Following a yearly tradition, *Science's* editors and news staff have selected one scientific Breakthrough of the Year and nine runners-up – and have also highlighted some areas to watch for 2012. [Access to articles may require [membership or a subscription](#).]

WINNER

### HIV Treatment as Prevention

J. Cohen

The antiretroviral drugs used to treat HIV-infected people also dramatically reduce HIV transmission rates, a finding that may influence the strategies used by health



One discovery, reported in November, is the sighting of pristine clouds of hydrogen. The clouds match the chemistry of much older primordial gas from the first few hundred million years after the big bang, before stars formed. **The other discovery is a small star in the Milky Way's halo whose concentration of “metals” (elements heavier than helium) is about 1/10,000 that of the sun.** This star is practically devoid of metals, just like the universe's earliest stars, which are believed to have been hundreds of times as massive.



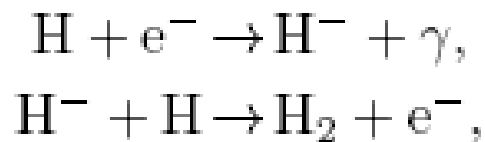
- If the process of first generation star formation is similar to the one believed to occur in present day stellar associations.
- Many small mass stars form before massive stars explode as SNe II, polluting the ambient ISM.
- One would expect Pop. III stars with  $0.8-0.9 M_{\odot}$ .

# Formation of the first stars

- The **absence** of heavy elements and therefore of dust.
- The cooling of the primordial gas depends only on hydrogen in its atomic and molecular form.

$$M_J \approx \frac{\pi k_B T}{Gm} L$$

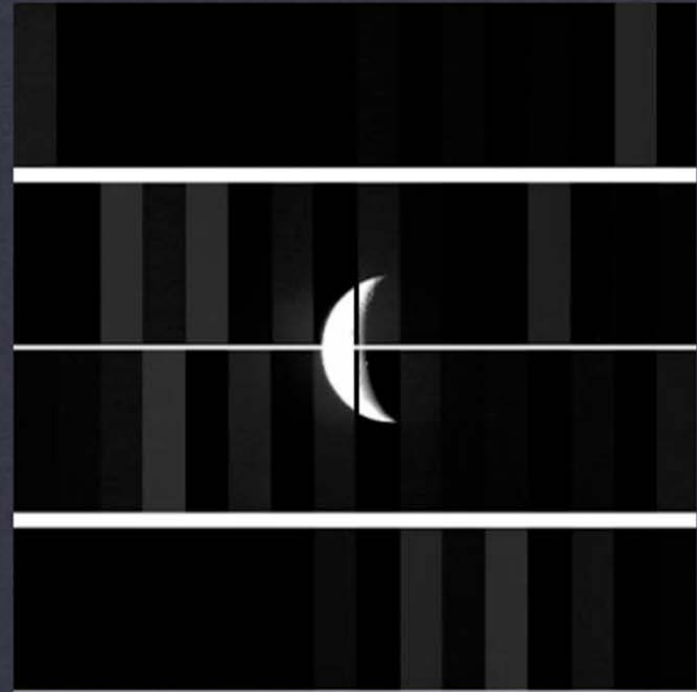
- Cools via H<sub>2</sub> *rotational* and *vibrational* line emission.



- Results from recent numerical simulations of the collapse and fragmentation of primordial gas clouds suggest that the first stars were **predominantly very massive, typical masses  $M_* \geq 100M_{\odot}$ , life times of  $\sim 10^6$ yr.**
- The failure to find any 'living' Pop. III star in the Galaxy is not surprising.
- They all would have died a long time ago.

- Results from recent numerical simulations of the collapse and fragmentation of primordial gas clouds suggest that the first stars were **predominantly very massive, typical masses  $M_* \geq 100M_\odot$ , life times of  $\sim 10^6$ yr.**
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## 5. Photometric surveys



**SkyMapper's Southern Sky Survey**

# SkyMapper

Keller et al. 2007

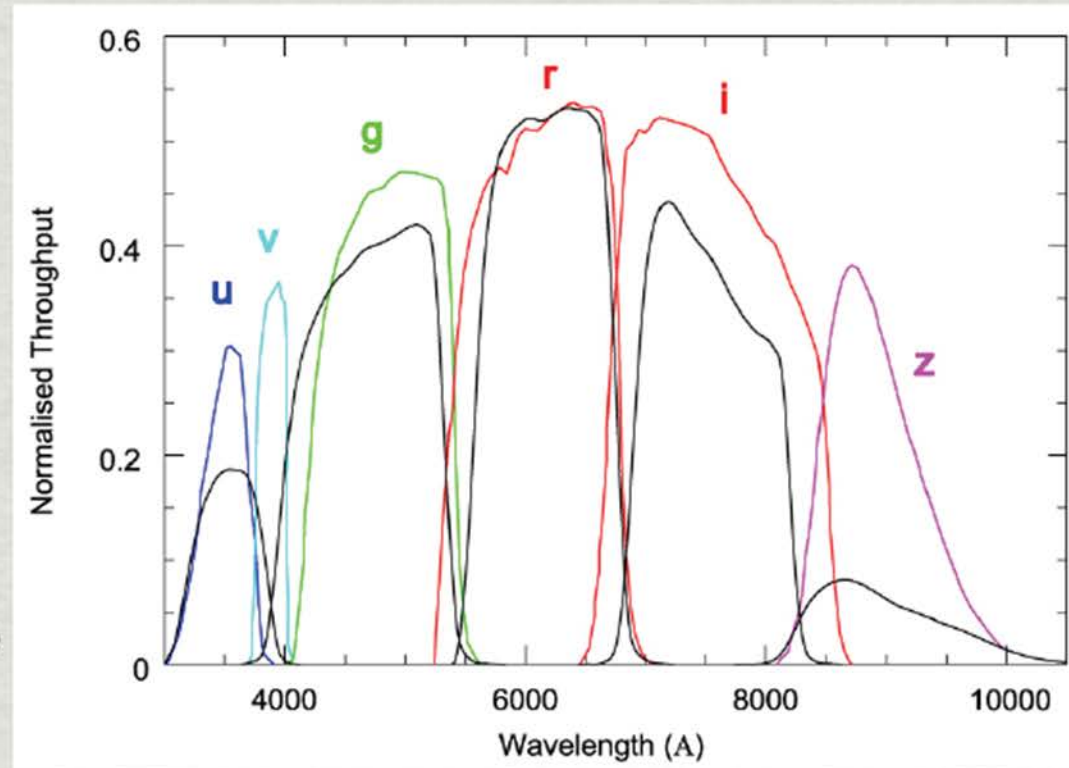
## The SkyMapper Facility

- \* 1.3m modified Cassegrain with a 5.7 square degree field of view
- \* Sited at the Australian National University's Siding Spring Observatory
- \* Fully automated, remote facility
- \* Data transferred via Gigabit link to ANU
- \* Aiming for science operation late 2010
- \* To conduct the Southern Sky Survey:
  - Five year
  - Multi-colour (6 filters)
  - Multi-epoch (6 exposures, each filter)
  - entire southern sky to  $g \sim 23$ rd
- \* A mosaic of 32 2kx4k CCDs.
- \* 0.5" per pixel = 5.7 square degrees fov.
- \* Using new STARGRASP controllers
- \* Readout in ~15 seconds
- \* Readnoise  $\sim 5e^-$  @ 15 seconds
- ➔ 8000 square deg. per night in rapid mode

# SkyMapper's niche

## Stellar Astrophysics

- ✳ Design: half of our sample are stars
- ✳ Galaxies well served by broadband photometry - stars are different their information content is primarily in the blue
- ✳ Optimised design to recover the fundamental stellar parameters:  $T_{\text{eff}}$ ,  $\log g$ ,  $[\text{Fe}/\text{H}]$



# Bessell et al. 2011

## fabricating large colored glass filters

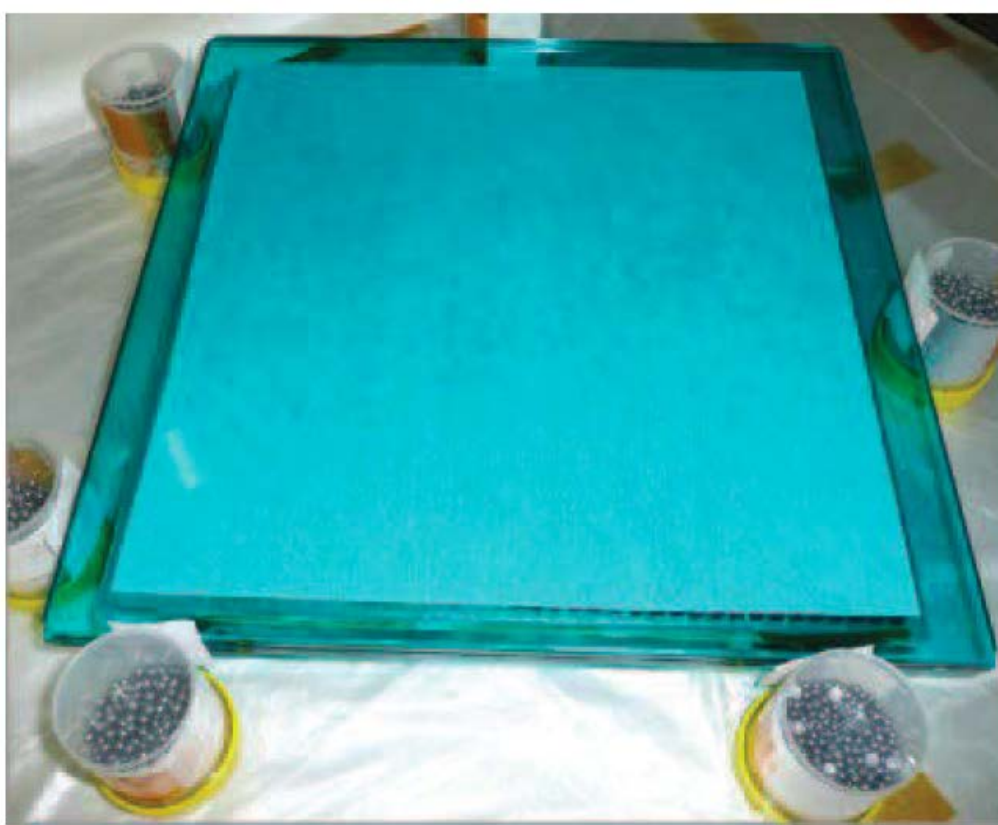


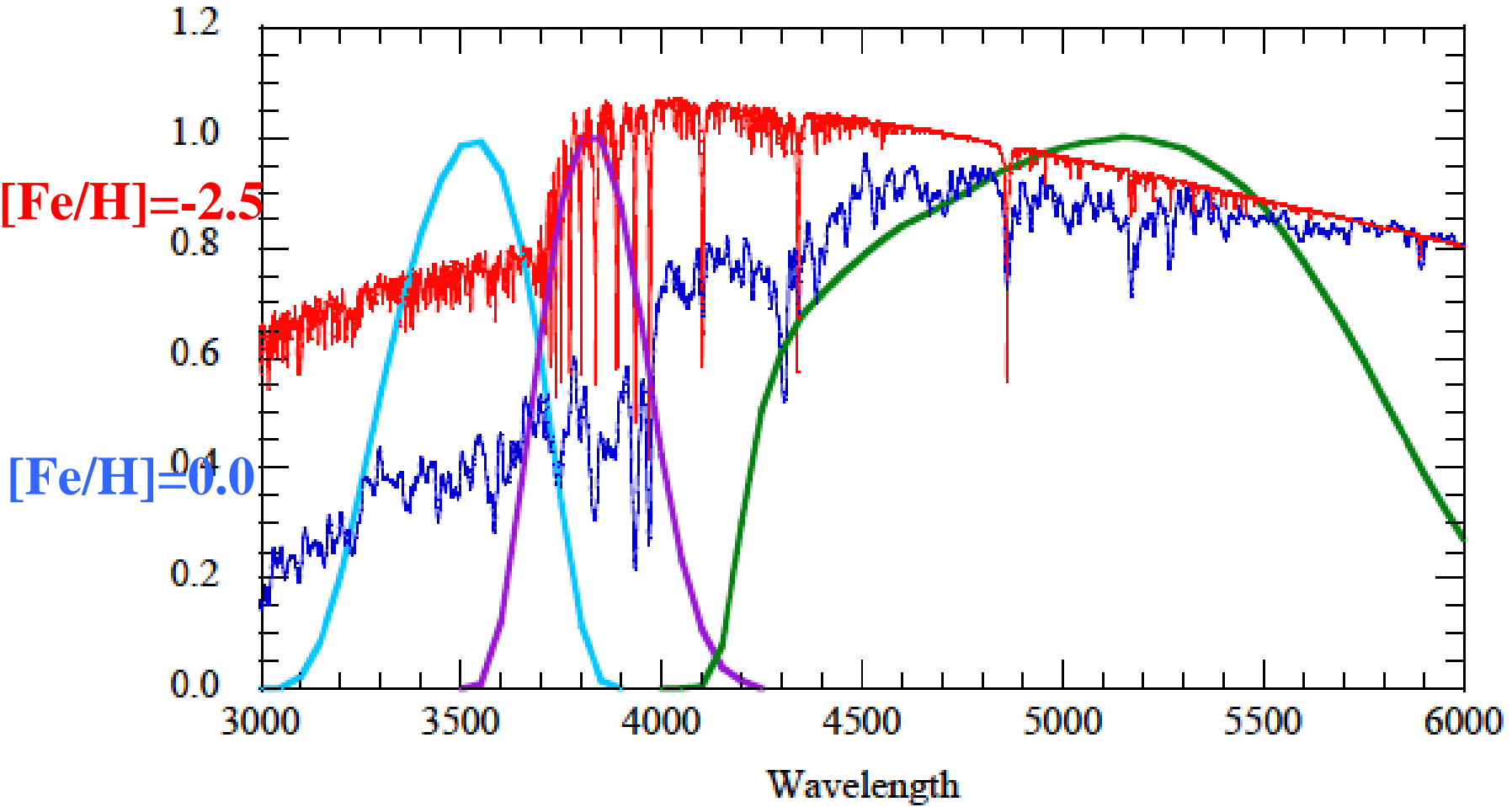
Fig. 1.— Gluing the g filter



Fig. 2.— The last mylar shim in place while gluing the u filter



# u v g and stellar spectra

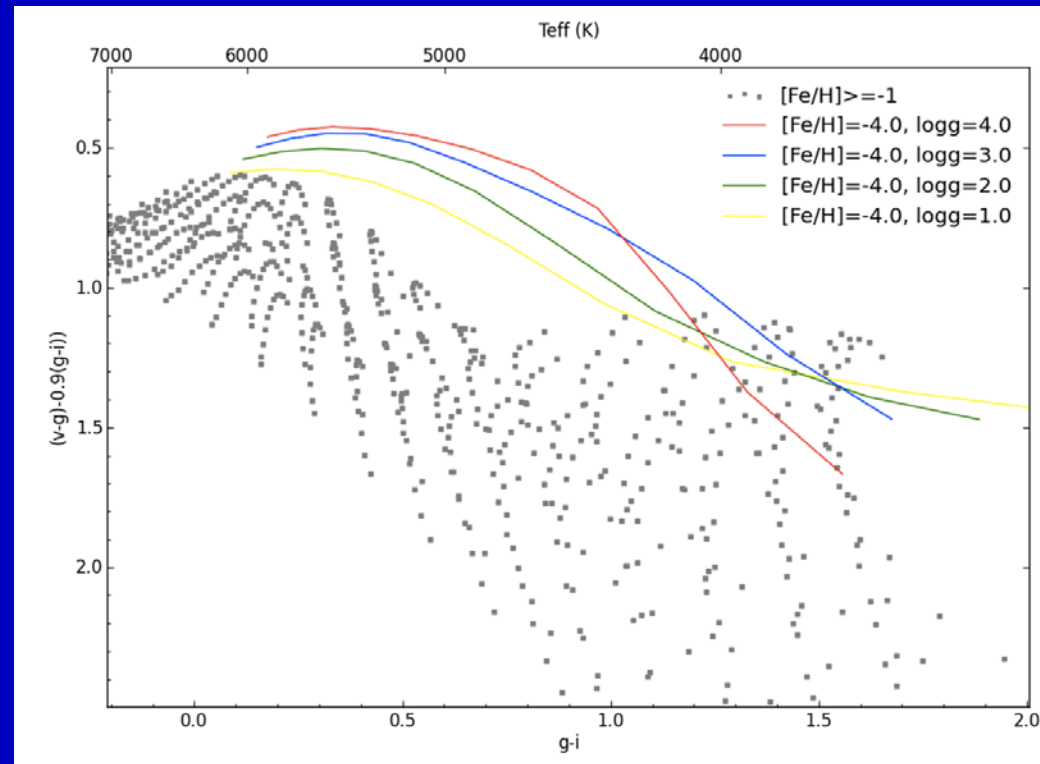


Spectra of a  $[Fe/H] = -2.5$  and  $0.0$  solar-type star with the u v g bands superimposed

# v-g vs. [Fe/H]

- Stellar colors

- Effective temperature
- Gravity
- [Fe/H]



## ARTICLE PREVIEW

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NATURE | LETTER



# A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36–670839.3

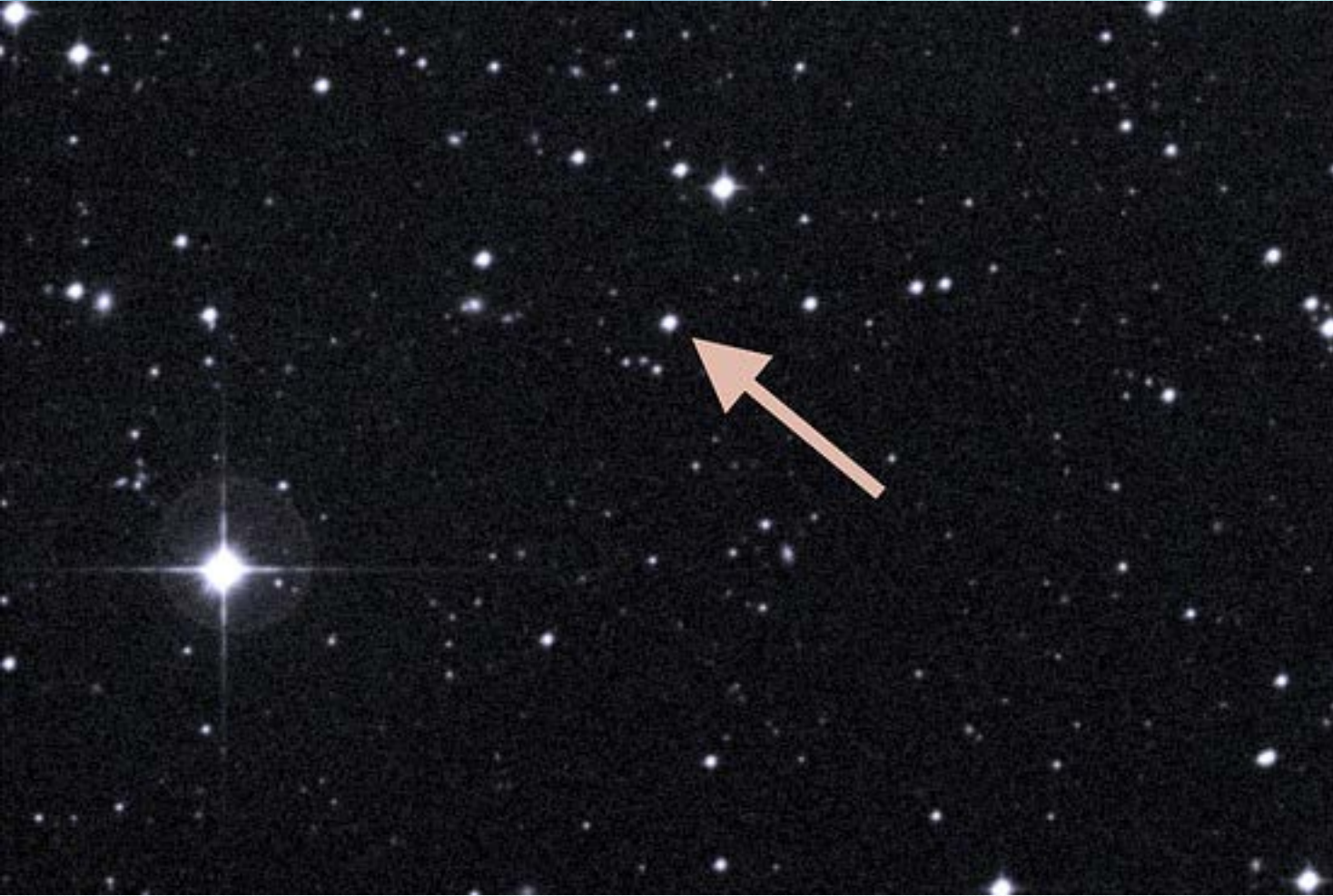
S. C. Keller M. S. Bessell A. Frebel A. R. Casey M. Asplund H. R. Jacobson K. Lind J. E. Norris D. Yong A. Heger Z. Magic G. S. Da Costa B. P. Schmidt P. Tisserand

[Affiliations](#) | [Contributions](#) | [Corresponding author](#)

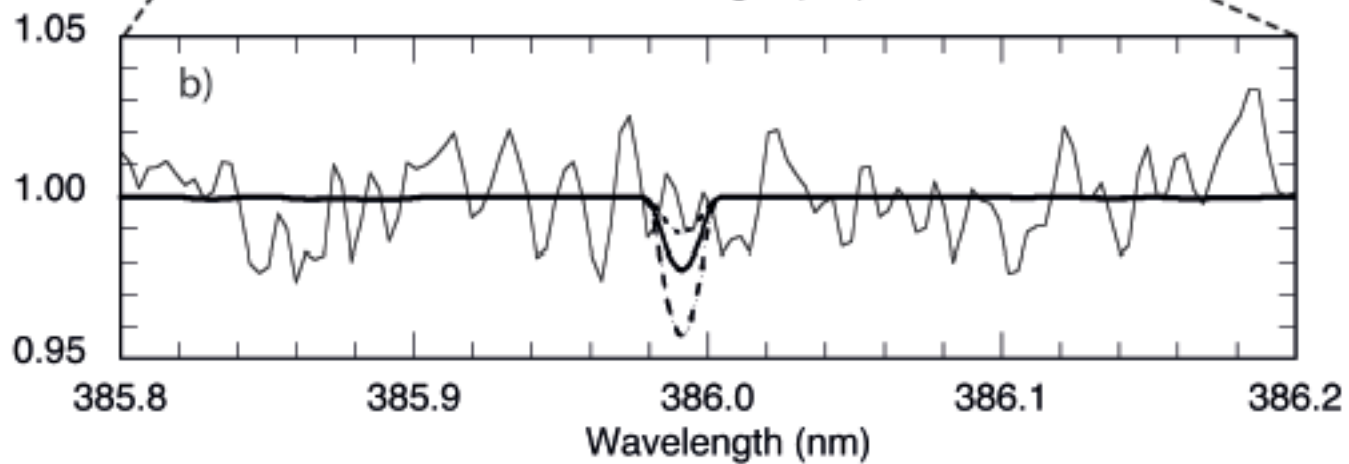
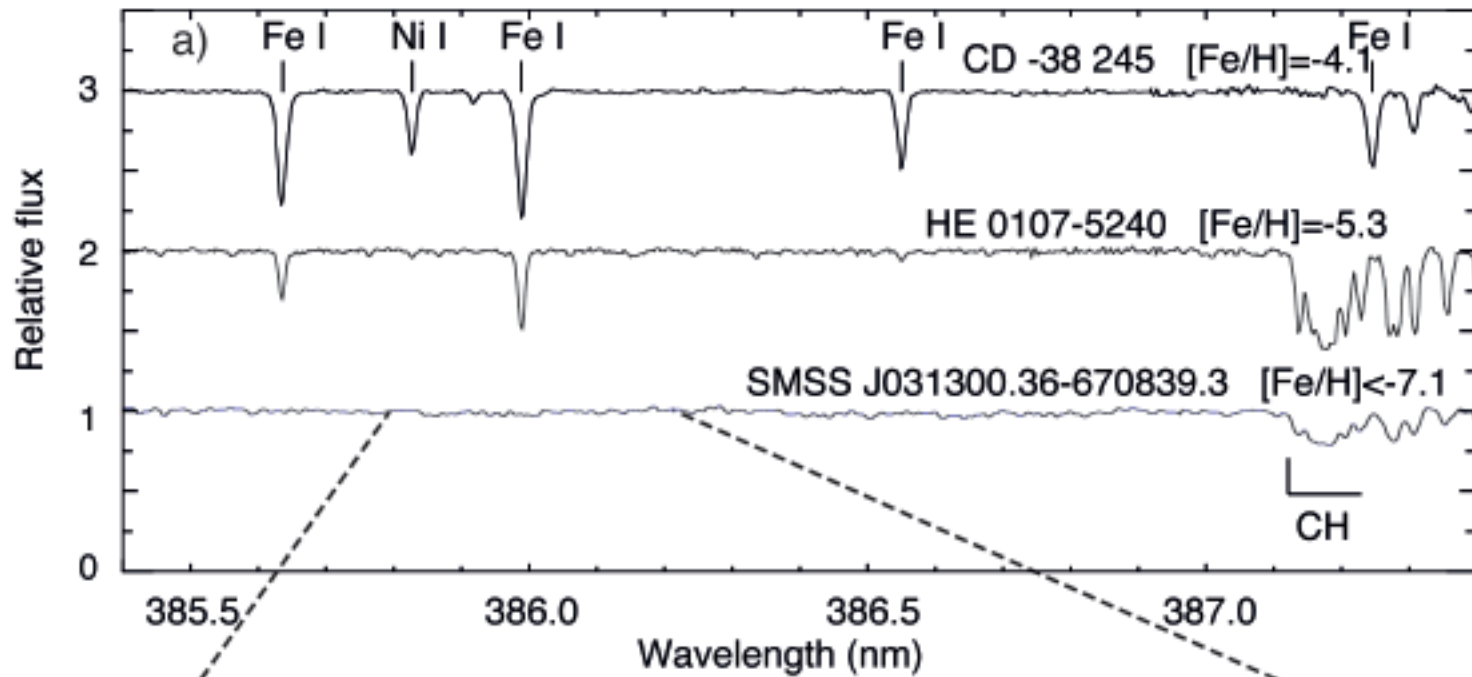
*Nature* (2014) | doi:10.1038/nature12990

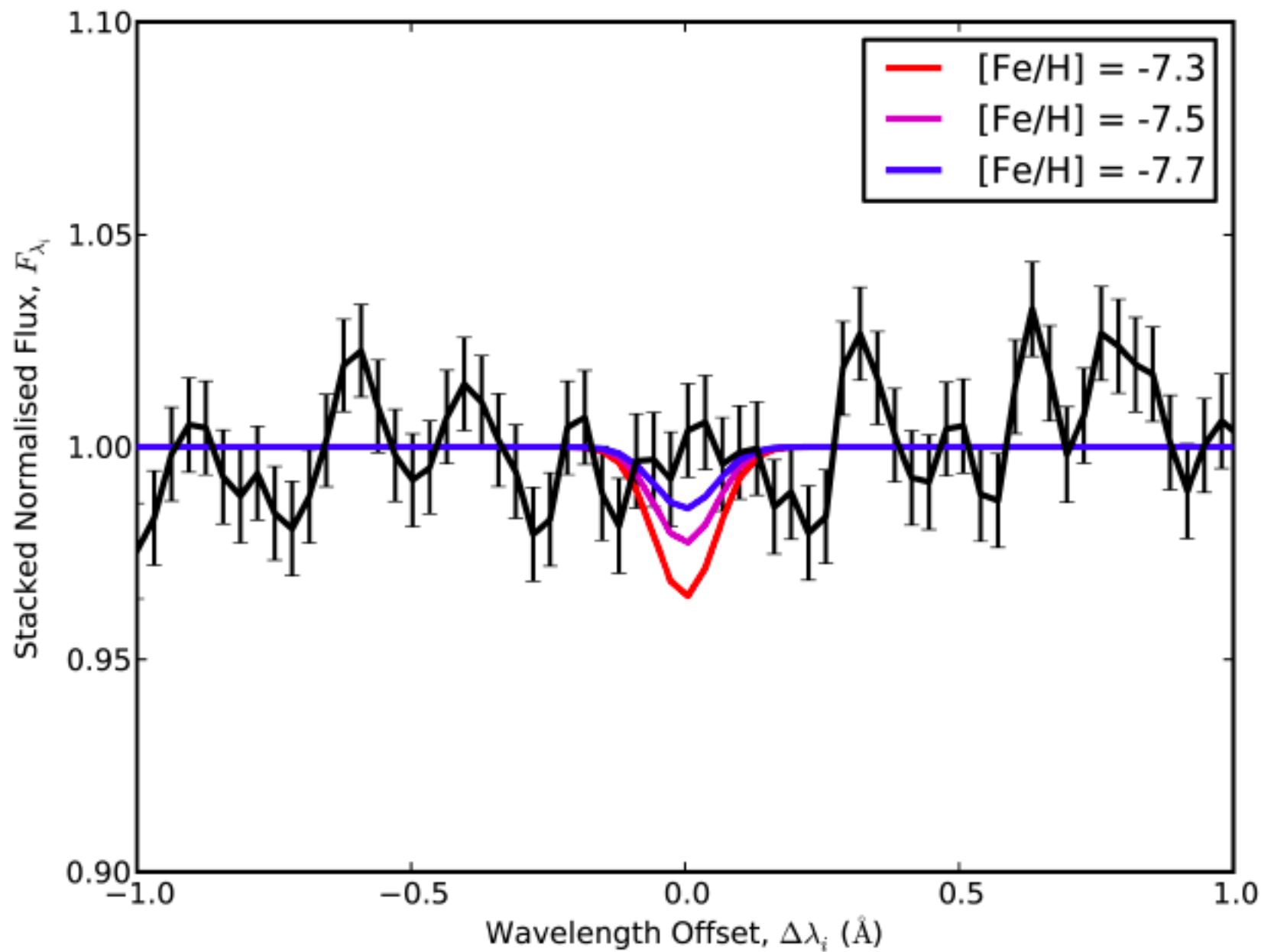
Received 09 July 2013 | Accepted 05 December 2013 | Published online 09 February 2014

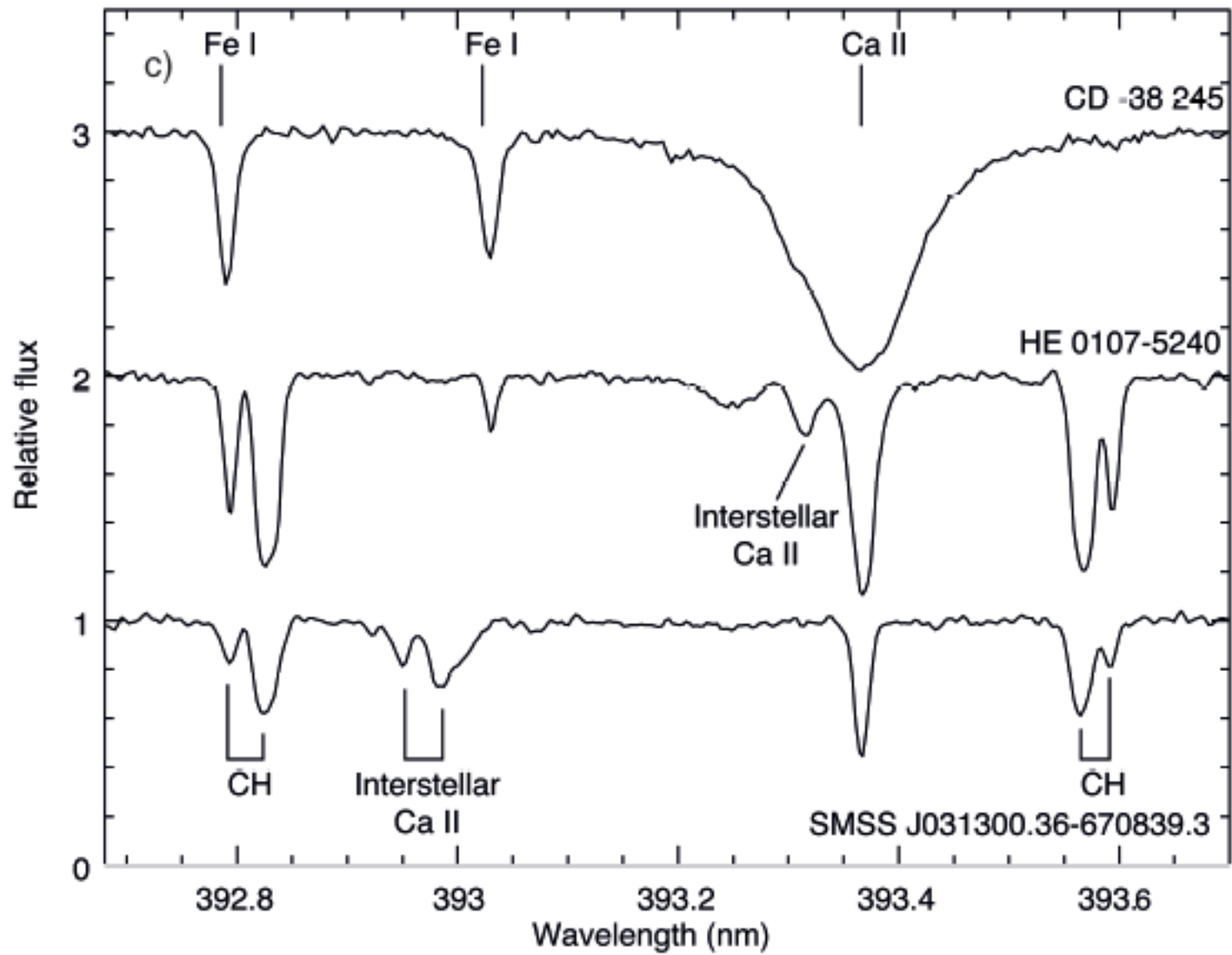
Astroph 1402.1517



R.A. = 03:13:00.4  
Dec. = -67:08:39  
V = 14.7



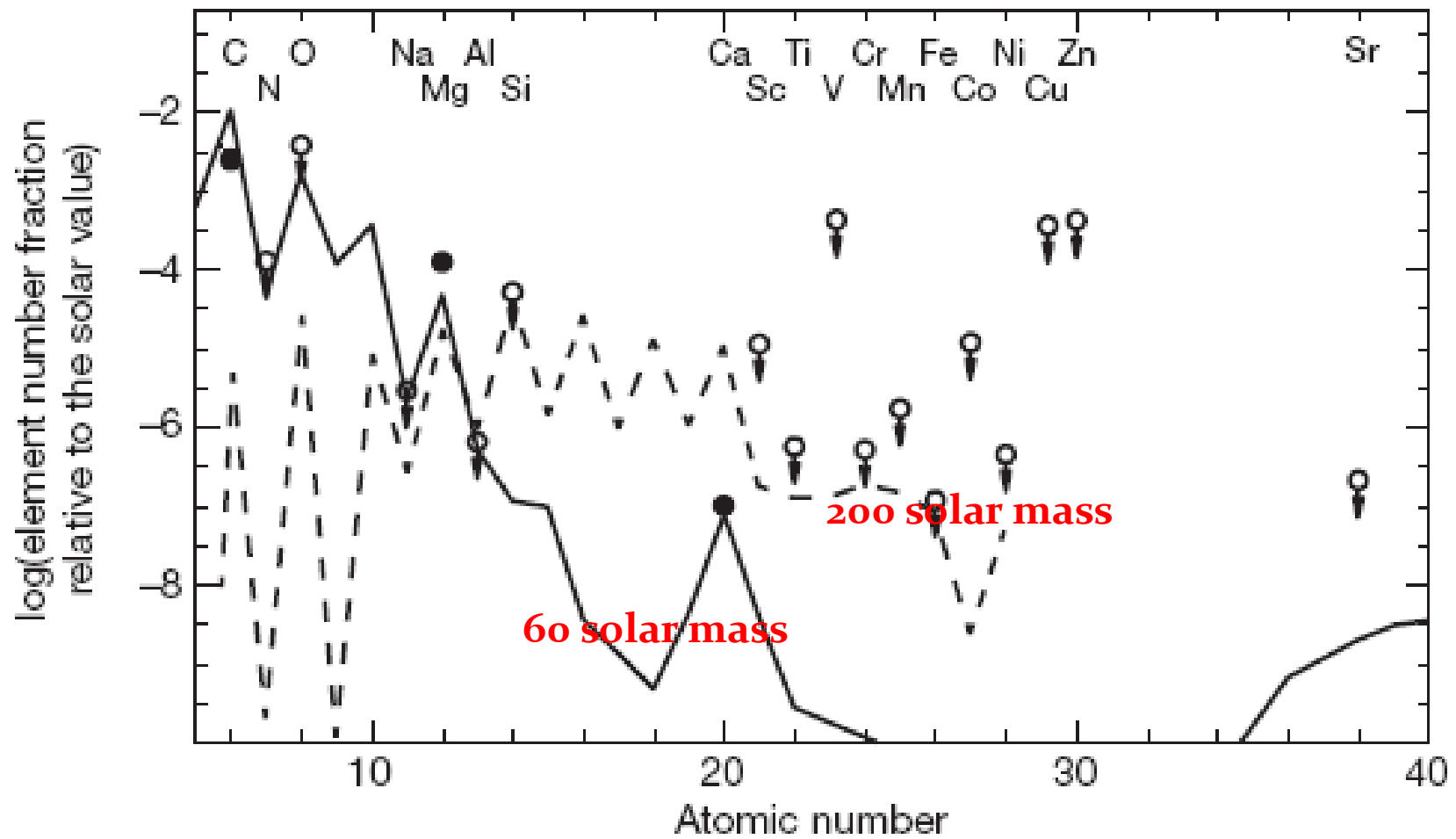




**Table 1 Chemical abundances of SMSS 0313-6708**

Element	$[X/H]_{1-d, LTE}$	$[X/H]_{<3-d>}$
Li I	0.7 <sup>λ</sup>	0.7 <sup>1λ</sup>
C (CH)	-2.4	-2.6 <sup>a</sup>
N (NH)	<-3.5	<-3.9 <sup>a</sup>
O I	<-2.3	<-2.4 <sup>a</sup>
Na I	<-5.5	<-5.5 <sup>b</sup>
Mg I	-4.3	-3.8 <sup>b</sup>
Al I	<-6.2	
Si I	<-4.3	
Ca II	-7.2	-7.0 <sup>b</sup>
Sc II	<-5.0	
Ti II	<-6.3	
V II	<-3.3	
Cr I	<-6.3	
Mn I	<-5.8	
Fe I	<-7.3	<-7.1 <sup>b</sup>
Co I	<-4.9	
Ni I	<-6.4	
Cu I	<-3.5	
Zn I	<-3.4	
Sr II	<-6.7	
Ba II	<-6.1	
Eu II	<-2.9	

Most iron-poor star !



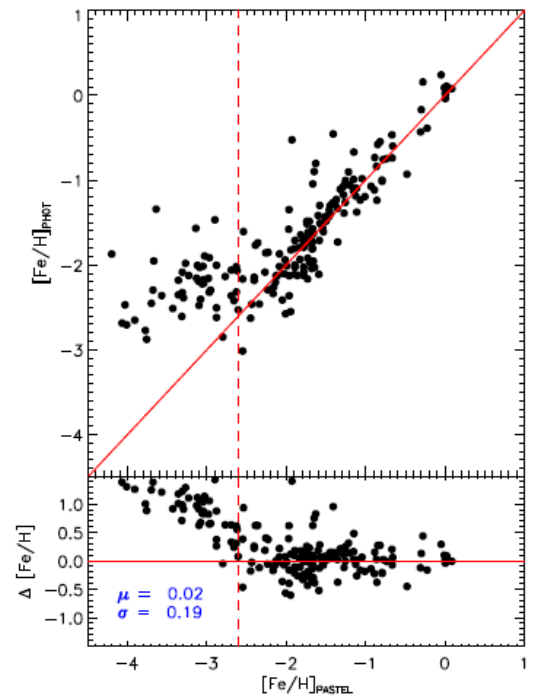
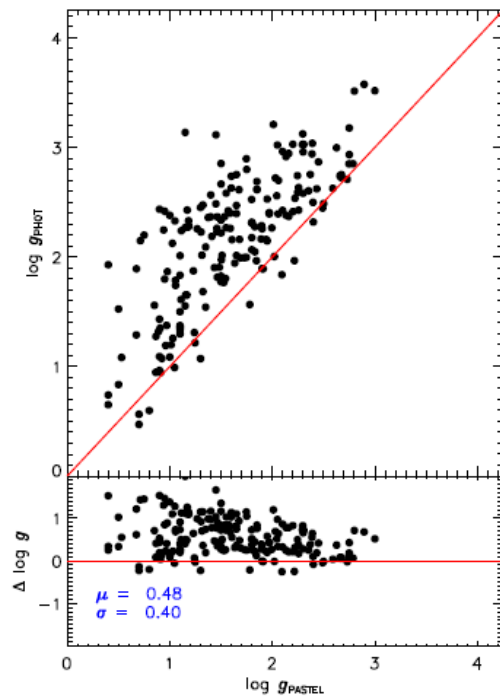
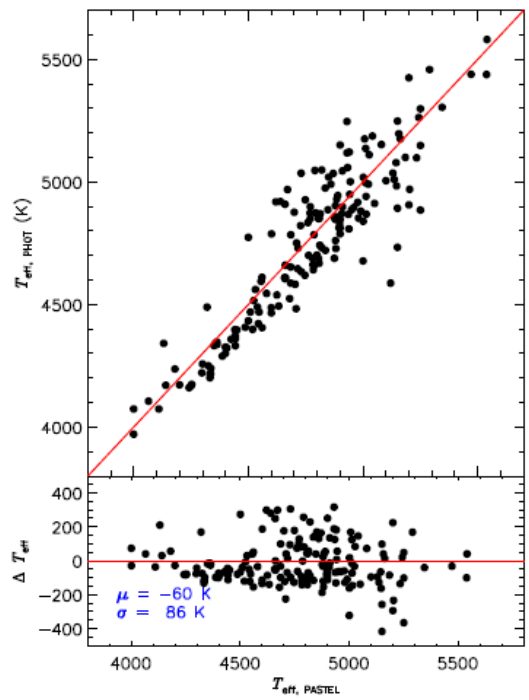
# Discovery of a **second-generation** star from the early universe

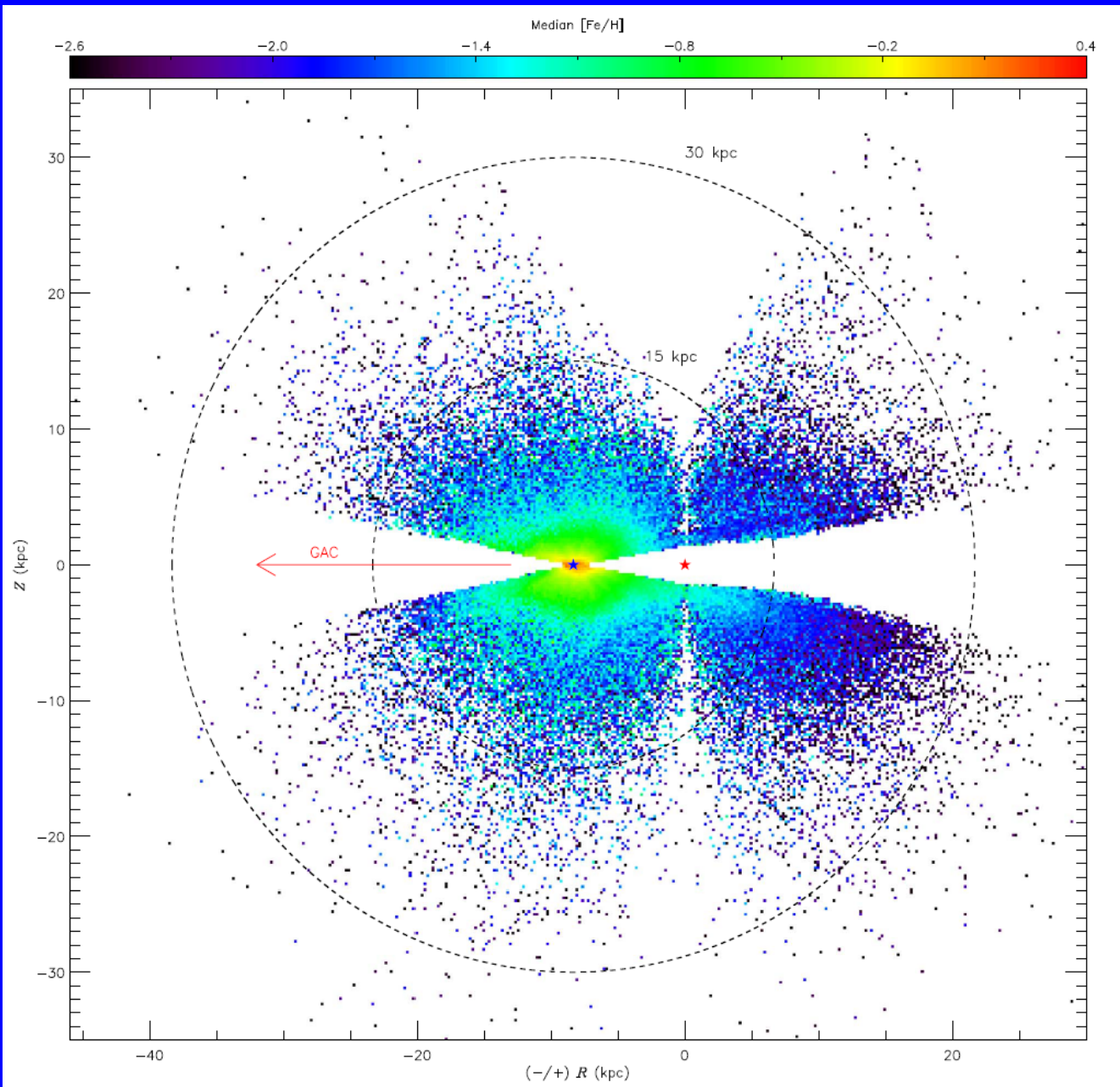
- **‘Based on a comparison of its abundance pattern with those of models, we conclude that the star was seeded with material from a single supernova with an original mass of ~60 solar mass.**

Milky Way Tomography with the SkyMapper Southern Survey.  
I. Atmospheric Parameters and Distances of One Million Red Giants

Huang et al. 2019

- developed a photometric method to select red giant stars and estimate their atmospheric parameters from the photometric colors provided by SkyMapper Southern Survey data.
- our method is capable of delivering atmospheric parameters with a precision of  $\sim 80$  K for  $T_{\text{eff}}$ ,  $\sim 0.18$  dex for  $[\text{Fe}/\text{H}]$ , and  $\sim 0.35$  dex for  $\log g$ .
- Using this method, the atmospheric parameters and distances of nearly **one million** red giant stars are derived from SMSS DR1.1.



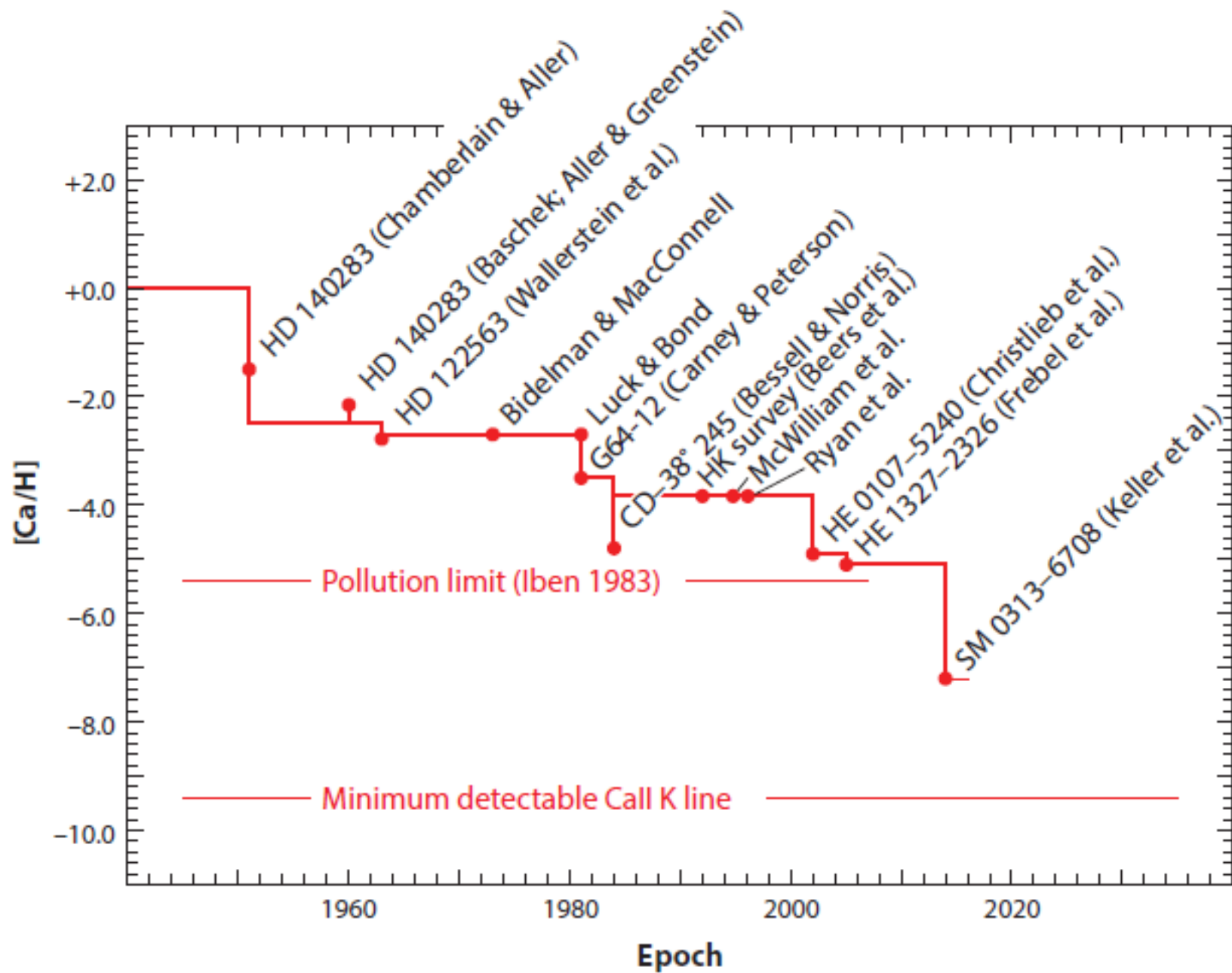


# 8 most iron-poor stars

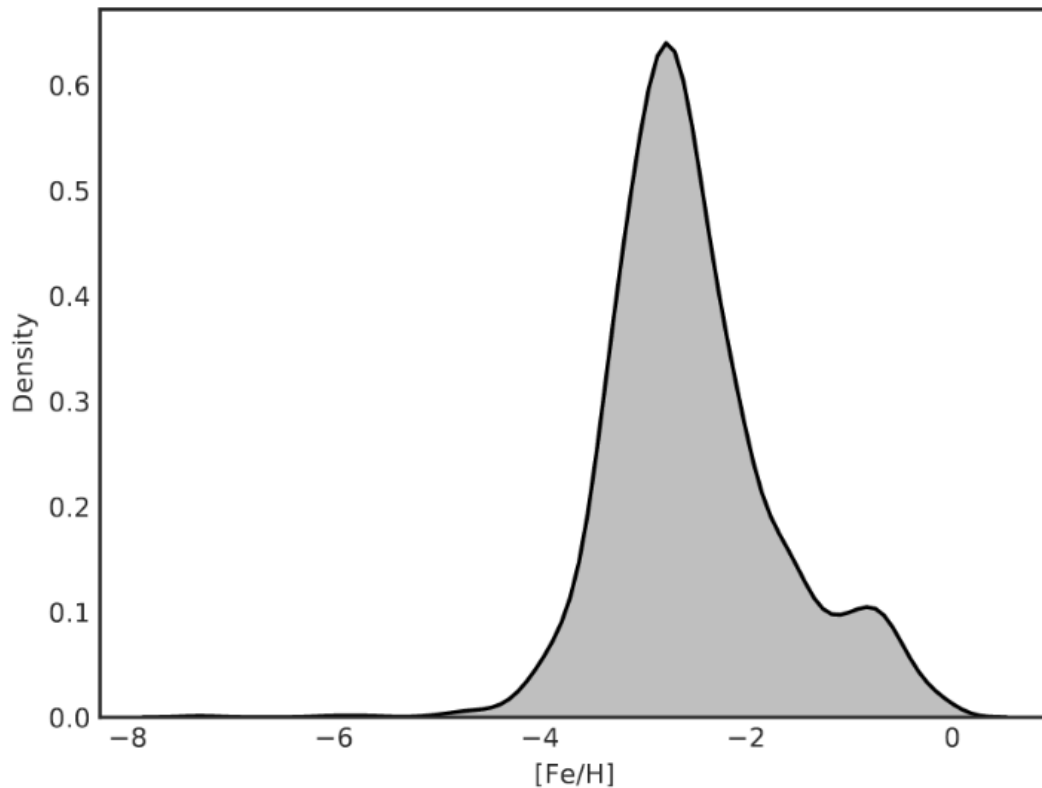
Most iron-poor

Object	RA (2000) Dec	$T_{\text{eff}}$	$\log g$	[Fe/H]	[C/Fe]	$V_r$ ( $\text{km s}^{-1}$ )
SM 0313–6708 <sup>a</sup>	03 13 00.4 –67 08 39.3	5,125	2.30	<–7.30	>+4.90	ND
HE 1327–2326	13 30 06.0 –23 41 49.7	6,180	3.70	–5.66	+4.26	64
HE 0107–5240	01 09 29.2 –52 24 34.2	5,100	2.20	–5.39	+3.70	44
SD 1035+0641 <sup>a</sup>	10 35 56.1 +06 41 44.0	6,262	1.5	<–5.1	>3.5	–70
HE 0557–4840	05 58 39.3 –48 39 56.8	4,900	2.20	–4.81	+1.65	212
SD 1742+2531 <sup>a</sup>	17 42 59.7 +25 31 35.9	6,345	1.5	–4.8	+3.6	–208
SD 1029+1729 <sup>a</sup>	10 29 15.2 +17 29 28.0	5,811	4.00	–4.73	<+0.93	–34
HE 0233–0343	02 36 29.7 –03 30 06.0	6,100	3.40	–4.68	+3.46	64

Most metal-poor



**JINAbase:** <http://jinabase.pythonanywhere.com/>  
Abohalima & Frebel 2018, arXiv:1711.04410

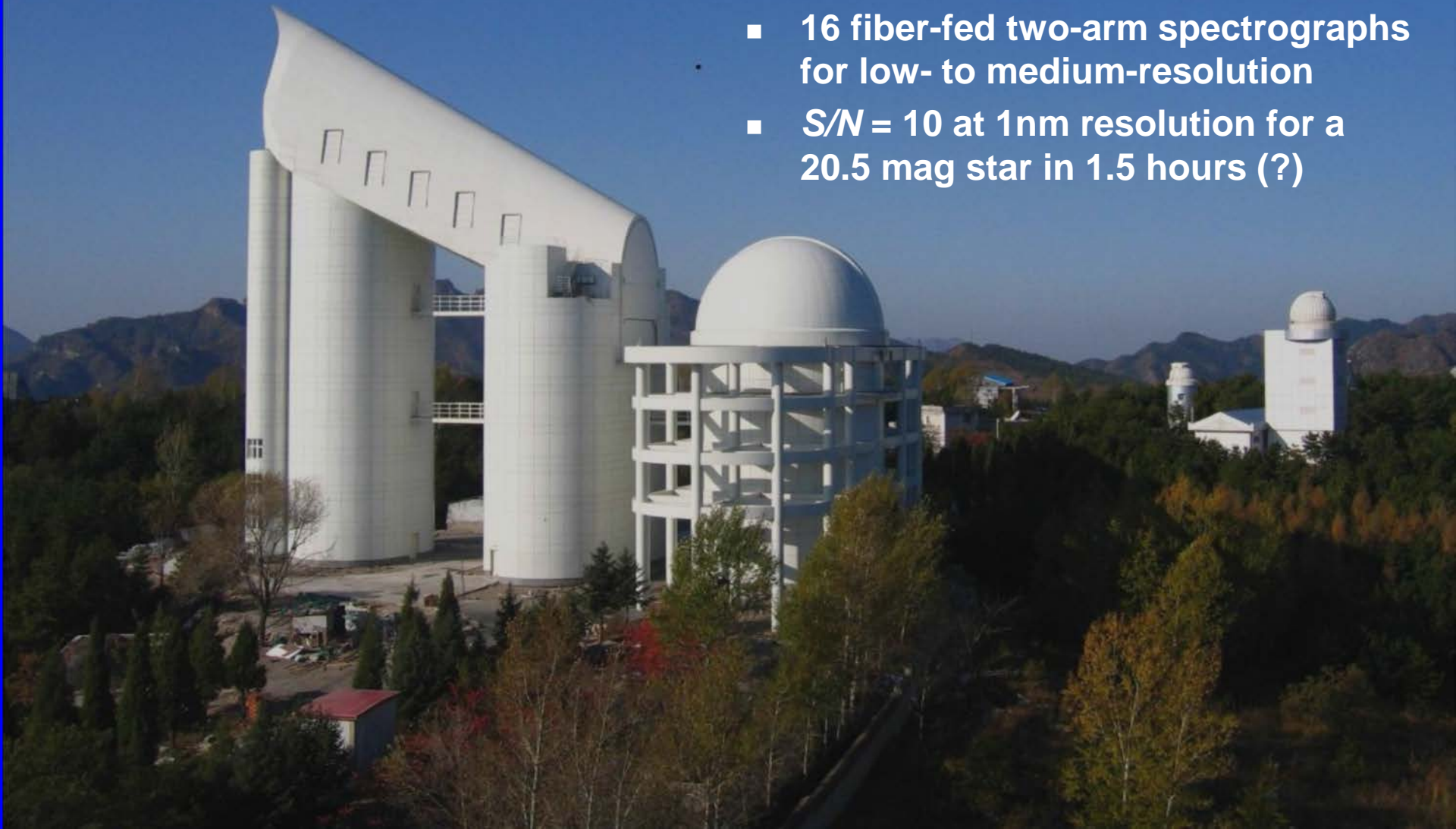


- 1658 stars
- 60% have  $[\text{Fe}/\text{H}] \leq -2.5$

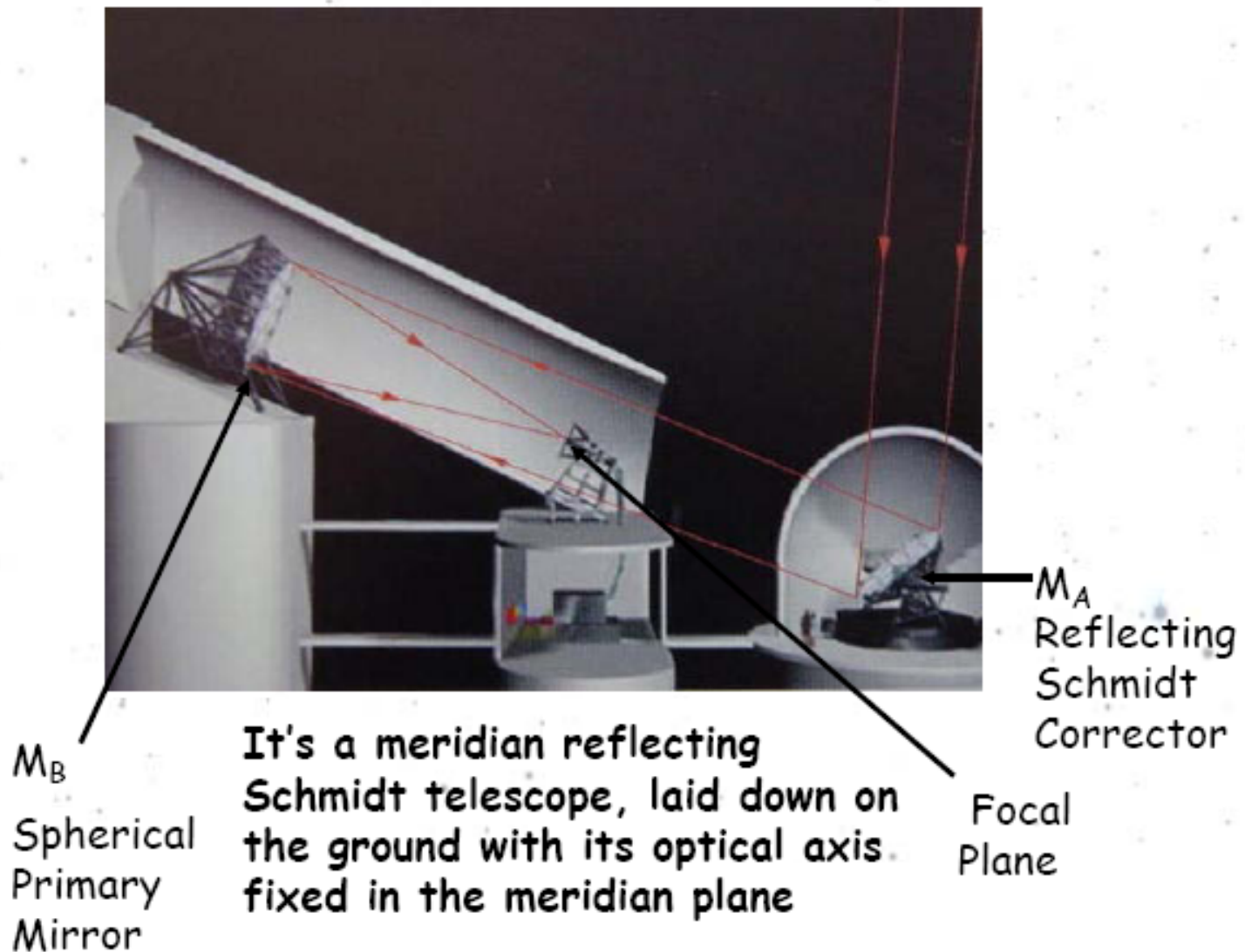
# LAMOST at Xinglong Station

[www.lamost.org](http://www.lamost.org)

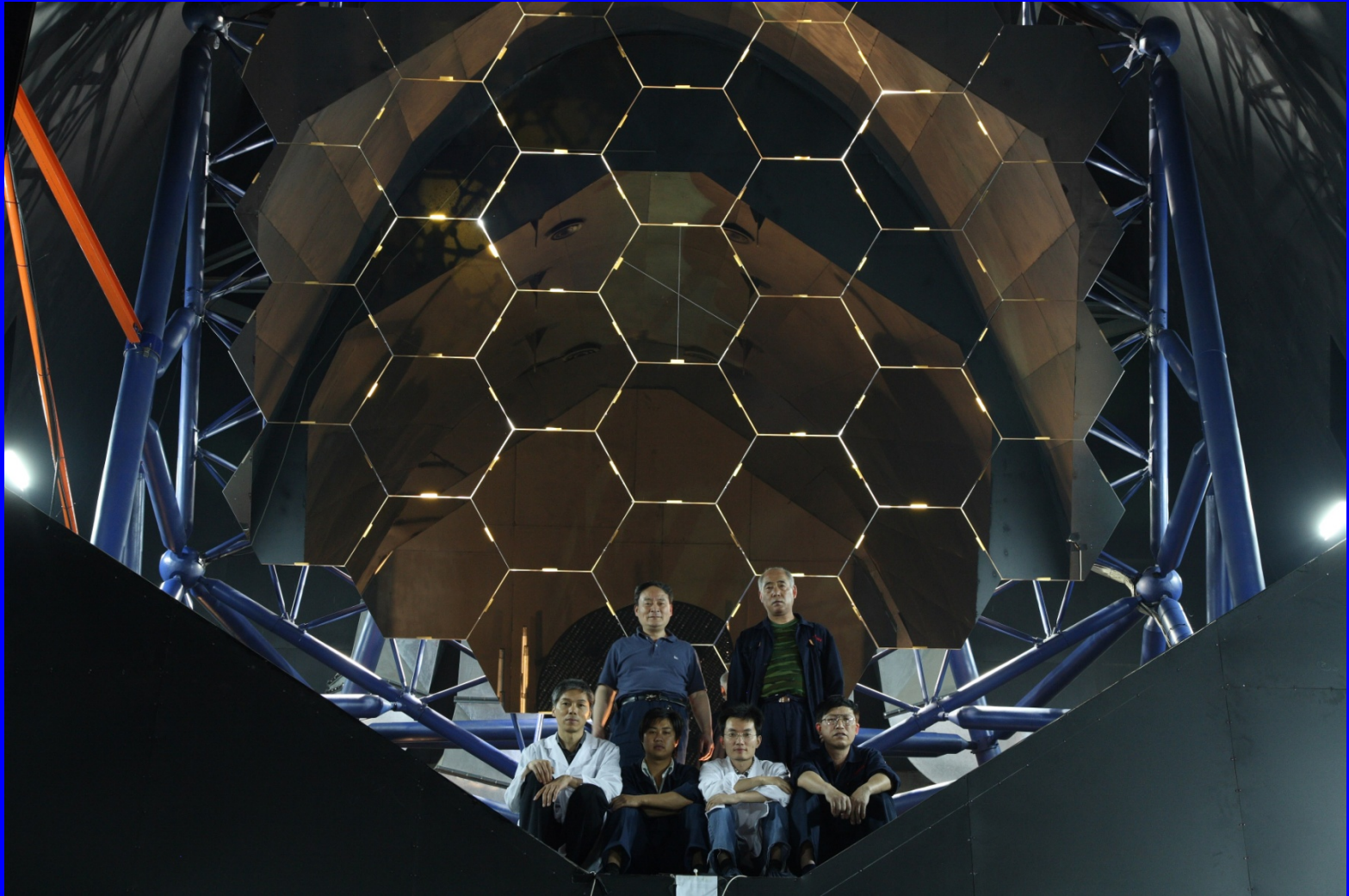
- Effective aperture: 4m
- 5° diameter field of view
- 4,000 fibers
- 16 fiber-fed two-arm spectrographs for low- to medium-resolution
- $S/N = 10$  at 1nm resolution for a 20.5 mag star in 1.5 hours (?)



# LAMOST optical design



# $M_B$ on 19 June 2008



# Instrument configurations

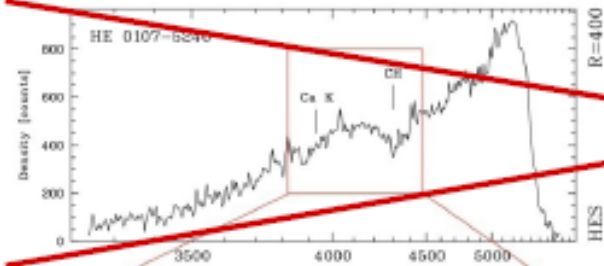
## Low-resolution mode

	Blue Arm		Red Arm	
	R	Wave. range (nm)	R	Wave. range (nm)
Full slit	1000	370-590	1000	570-900
1/2 slit	2000	370-590	2000	570-900

## Medium-resolution mode

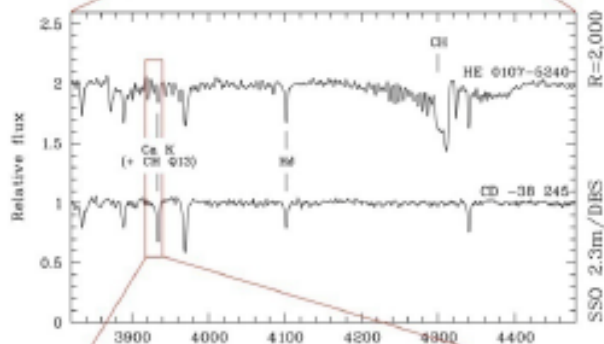
	Blue Arm		Red Arm	
	R	Wave. range (nm)	R	Wave. range (nm)
Full slit	5000	510-550	5000	830-890
1/2 slit	10000	510-550	10000	830-890

# The main observational steps

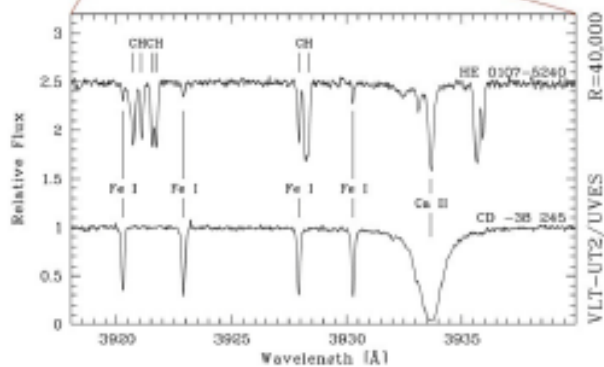


## 1. Candidate selection

Quantitative criteria based on Ca K line strength, *B-V* and *J-K* colours

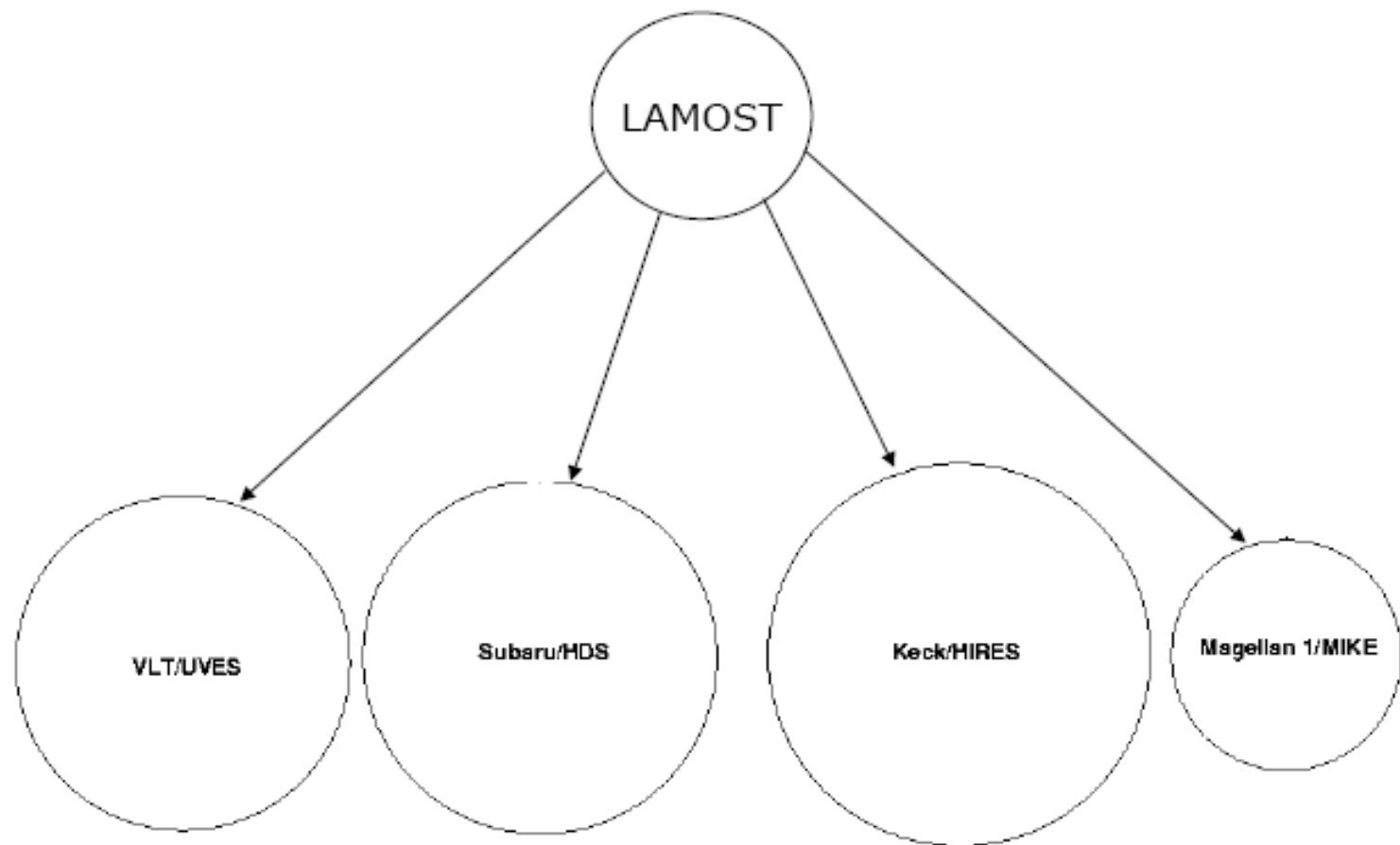


## 2. Confirmation of candidates with moderate-resolution spectroscopy (i.e., $R \sim 2000$ )

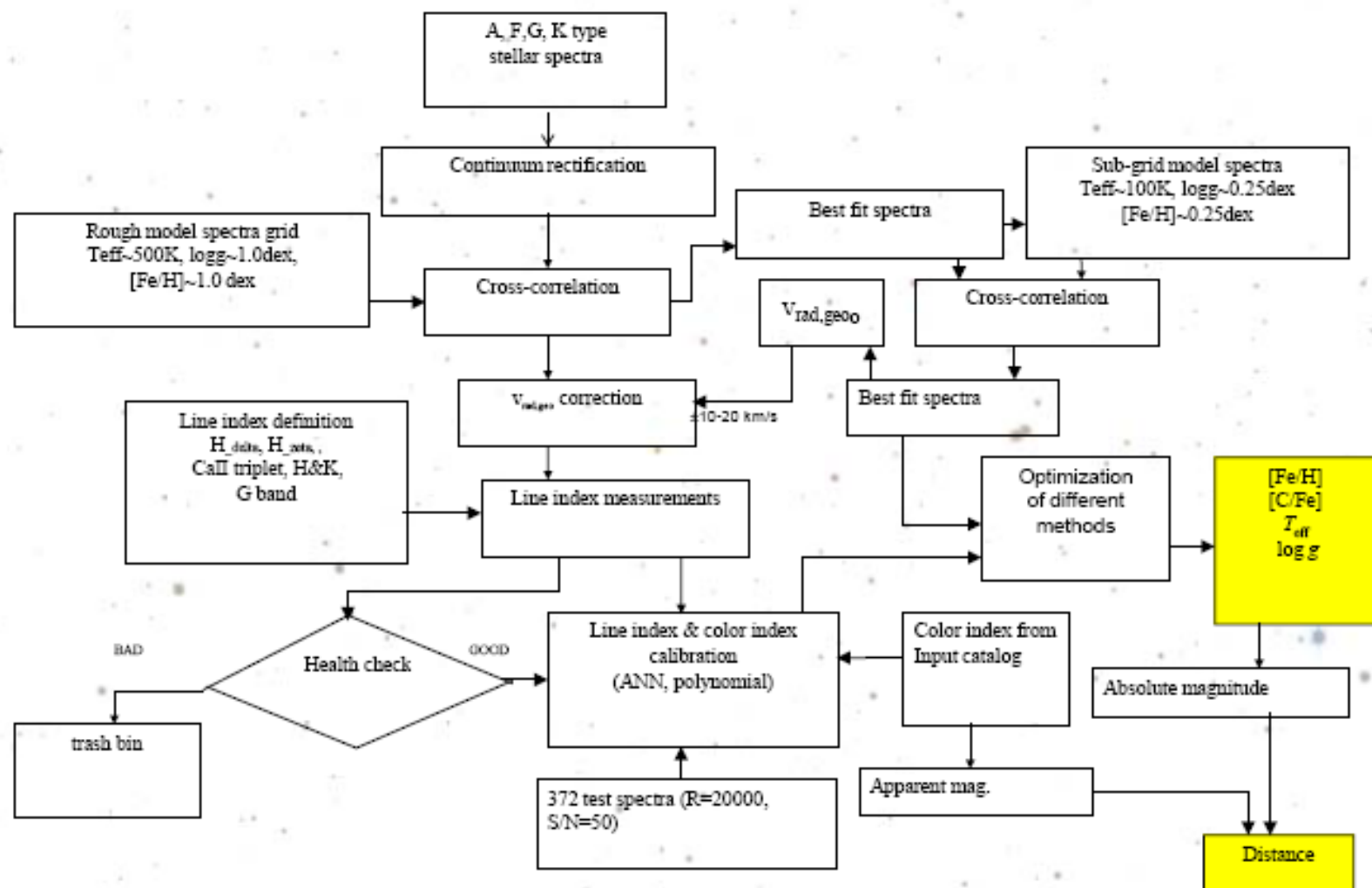


## 3. High-resolution spectroscopy (i.e., $R > 40,000$ ) for determination of abundances of elements

# The LAMOST survey for metal-poor stars



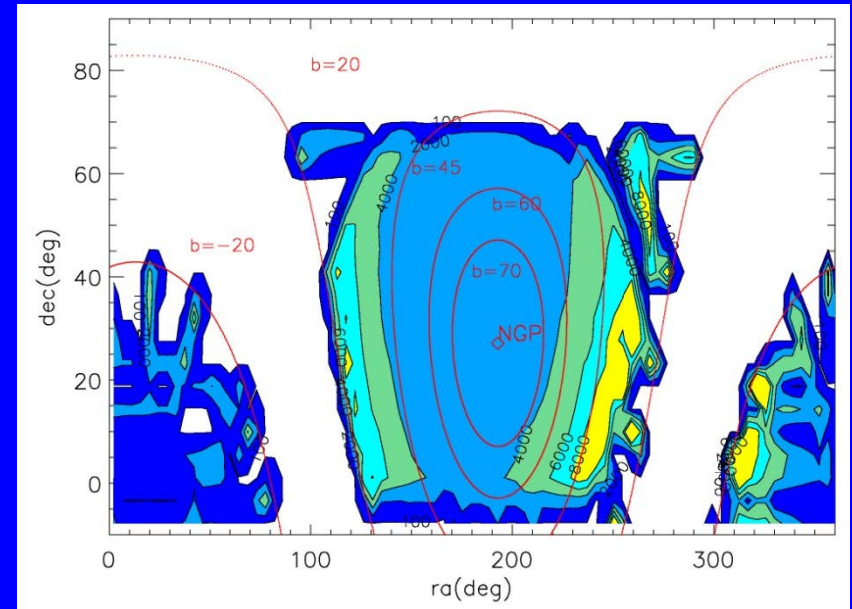
# Automated LAMOST Data Analysis Pipeline



# The LAMOST metal-poor star survey

- G. Zhao, N. Christlieb, H. Li, A. Luo, J. Zhao, et al.
- 5.1 million stars selected from SDSS DR7. Selection criteria:
  - $0.1 < (g-r)_0 < 1.0$
  - $g < 18.0$
  - $|b| > 20^\circ$ ,  $Z > 5$  kpc
  - $-10^\circ < \delta < 70^\circ$

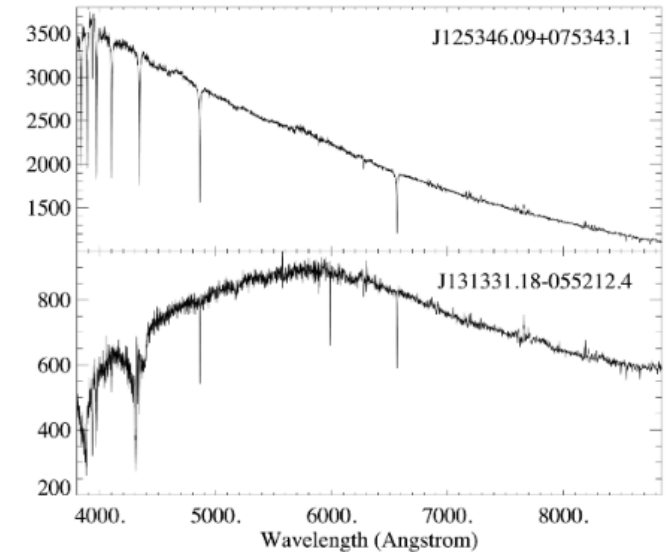
$R = 2000$ ;  $\lambda = 370\text{--}900$  nm



# Li, H.N. (2015a,b)

**Table 3**  
Adopted Stellar Parameters of the Program Stars

ID	MIKE Measurements				LAMOST Measurement		
	$T_{\text{eff}}$ (K)	$\log g$	[Fe/H]	$\xi$ ( $\text{km s}^{-1}$ )	$T_{\text{eff}}$ (K)	$\log g$	[Fe/H]
LAMOST J0006+1057	4520	0.6	-3.26	2.2	4800	1.6	-3.03
LAMOST J0102+0428	4540	0.6	-2.75	2.5	4940	1.2	-2.78
LAMOST J0126+0135	4330	0.1	-3.57	2.8	4810	1.2	-3.15
LAMOST J0257-0022	6330	4.2	-2.24	1.5	6260	3.6	-2.65
LAMOST J0326+0202	4700	1.1	-3.36	1.8	4830	1.8	-3.15
LAMOST J0343-0227	4790	1.5	-2.42	2.0	4795	1.8	-2.57
LAMOST J1626+1721	5930	3.6	-3.20	1.6	5830	3.4	-3.00
LAMOST J1709+1616	5780	3.5	-3.71	1.9	6070	3.0	-3.33



**Table 2.** Basic parameters of the two UMP stars.\*

ID	Subaru measurement				LAMOST measurement		
	$T_{\text{eff}}$ (K)	$\log g$	[Fe/H]	$\xi$ ( $\text{km s}^{-1}$ )	$T_{\text{eff}}$ (K)	$\log g$	[Fe/H]
LAMOST J125346.09+075343.1	$6030 \pm 135$	$3.65 \pm 0.16$	$-4.02 \pm 0.06$	$1.4 \pm 0.12$	6034	2.75	-3.97
LAMOST J131331.18-055212.4	$4750 \pm 94$	$1.60 \pm 0.21$	$-4.12 \pm 0.13$	$1.5 \pm 0.07$	4630	1.32	-4.23

# EMP and HMP stars expected to be found

Survey	Effective sky coverage	Effective mag limit	$N < -3.0$ (EMP)	$N < -5.0$ (HMP)
HES	6400 deg <sup>2</sup>	$B < 16.5$	200	2
SEGUE	1000 deg <sup>2</sup>	$B < 19$	1000	10
LAMOST	5,000 deg <sup>2</sup>	$B < 18.5$	5,000	50
SSS	20,000 deg <sup>2</sup>	$B < 18?$	5000	50
Gaia	40,000 deg <sup>2</sup>	$B < 19?$	40,000?	400?

- **These estimates are accurate only to within a factor of ~2!**
- Number of stars to be found in SEGUE will mainly be limited by number of fibers allocated for follow-up. Only about 10% of all candidates down to  $B = 19$  can be observed.
- Gaia requires extensive ground-based spectroscopic follow-up.

# Summary

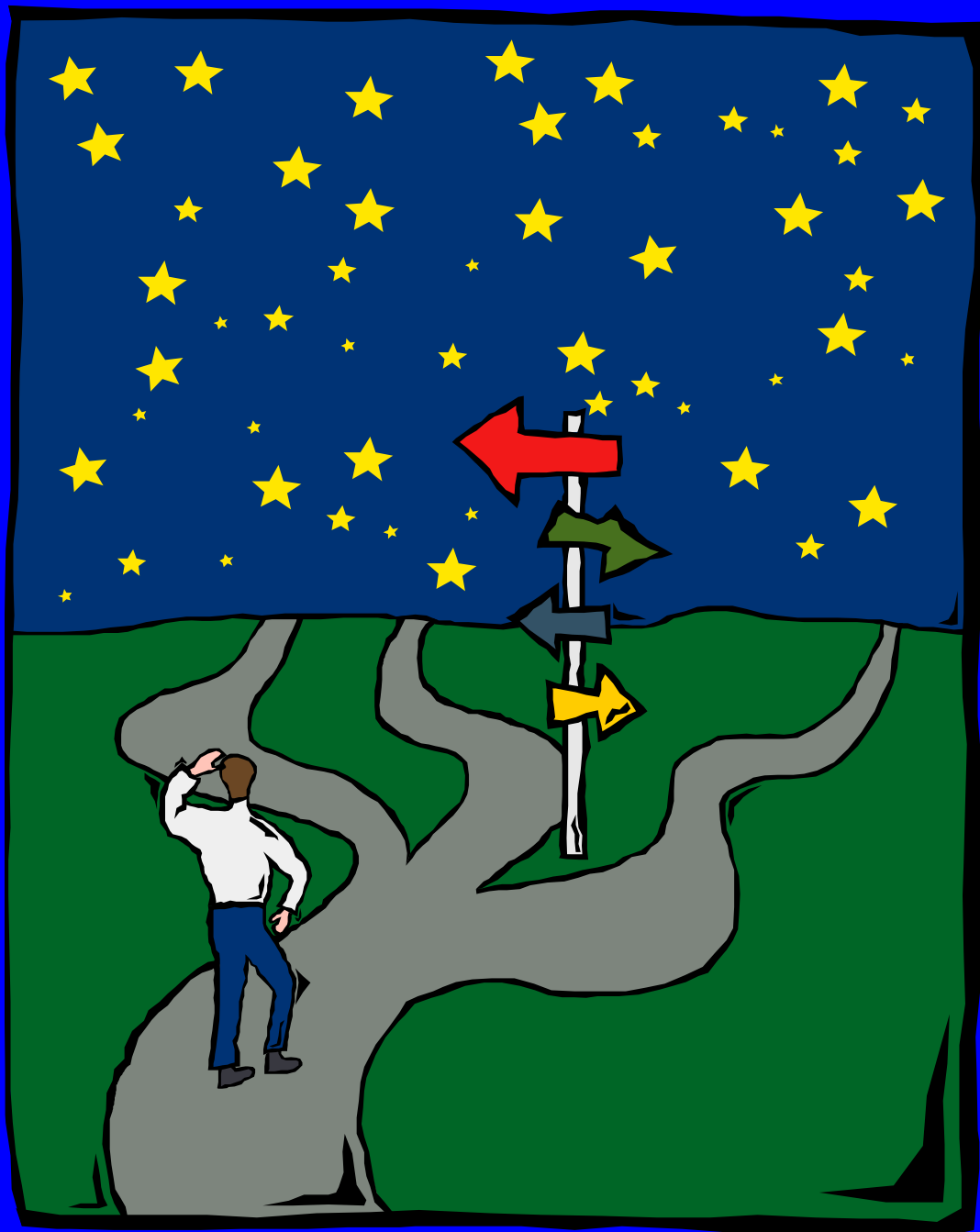
- It is expected that in the next decade, the sample of known metal-poor stars will be increased by 1-2 orders of magnitude.
- Detailed abundance analyses of these stars will lead to an improved understanding of the chemical evolution and formation of the Galaxy, the nature of the first stars, and star formation and nucleosynthesis processes in the early Universe.
- **Review paper:**  
Frebel & Norris, 2015, ARA&A, 53, 631

Cayrel(1996): *ARA&A*, 7,217

‘Can we hope to find a Pop. III star before  
year 2000?’

**No!**

Can we hope to find a Pop. III  
star before year **XXXX** ?



Thank You !