

Astronomy 353  
(Spring 2007)

Lecture 23:

# „The Oldest Stars in our Galaxy“

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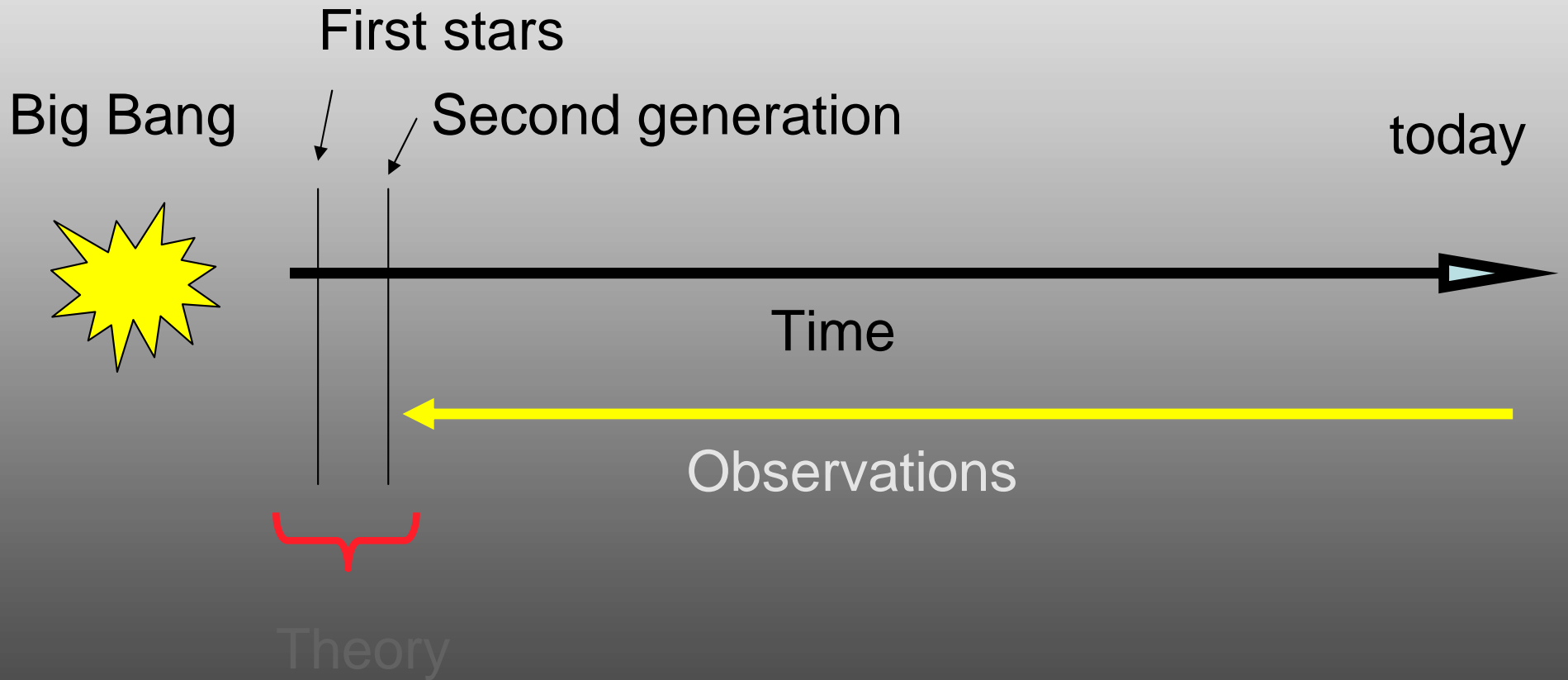
# Recap

- Formation of the first stars
- Stellar deaths

Q: What is left from the early Universe that we can still observe today?

A: A lot..! We call this near-field cosmology

# Cosmic timeline



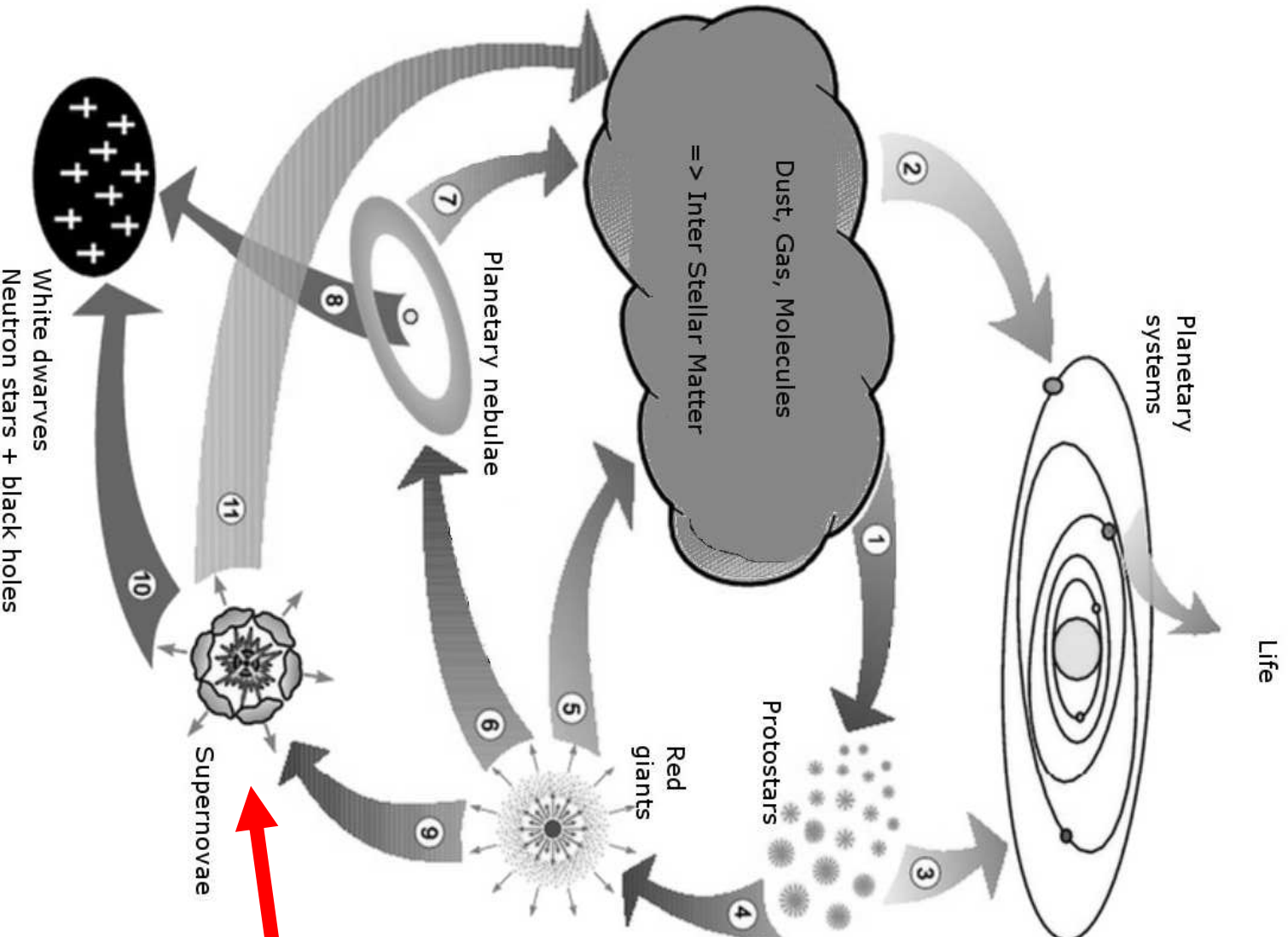
# We are Children of the Stars...!

- Elements are produced in stars and supernovae
- Successive built up of heavy elements in the Universe through “cosmic recycling”

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

=> We look for the stars with the least amount of elements heavier than H and He!

# Cosmic recycling



Zentrum fuer Astronomie und Astrophysik, TU Berlin

Heavy elements  
are produced  
here!

# Stellar Archaeology I

*Some definitions:*

*Metals = concerns all elements, except hydrogen and helium*

*Metal-poor star = Star with fewer metals than the Sun*

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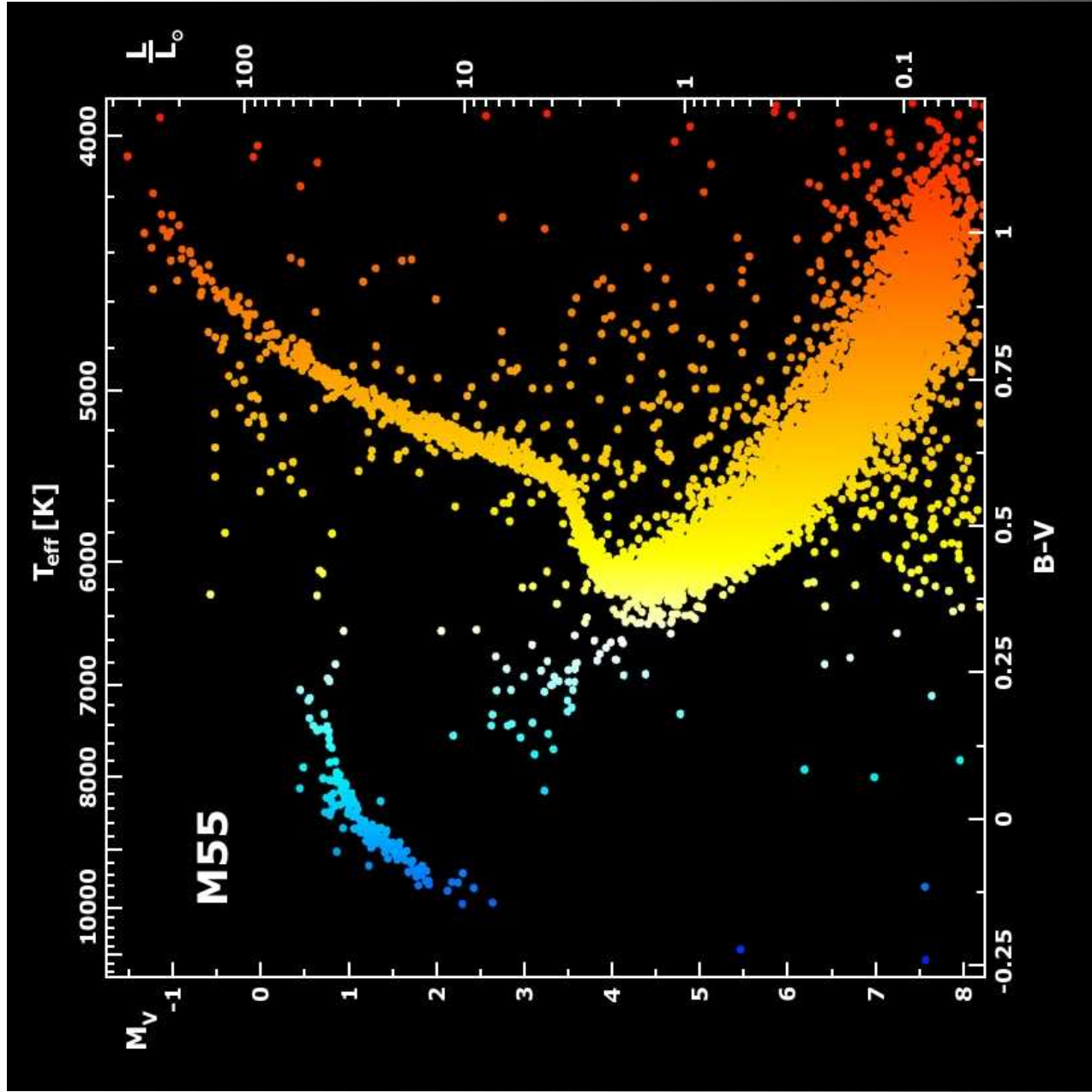
- Population I: Metallicity similar to that of Sun; young disk stars
- Population II: Lower metallicity (metal-poor); old halo stars
- Population III: Theoretical population; the very first generation of stars that formed after the big bang

# Stellar Archaeology II

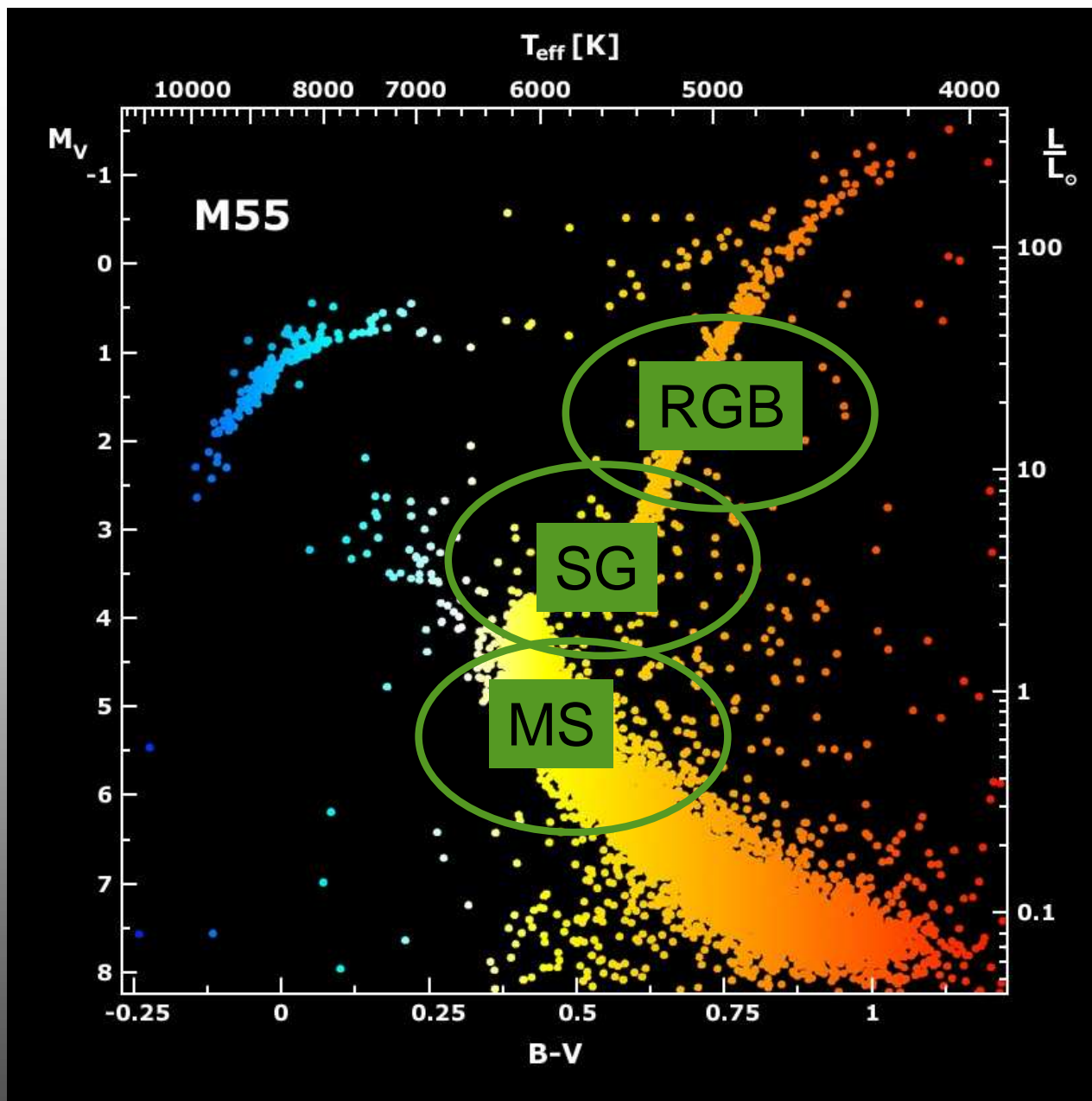
Why are metal-poor stars interesting?

- Chemical evolution of the Galaxy from the Big Bang until today
- “Snapshots of the early Universe”
- Nucleosynthesis processes can be studied
- Models of the first stars can be tested
- They are the “**closest relatives**” to the First Stars

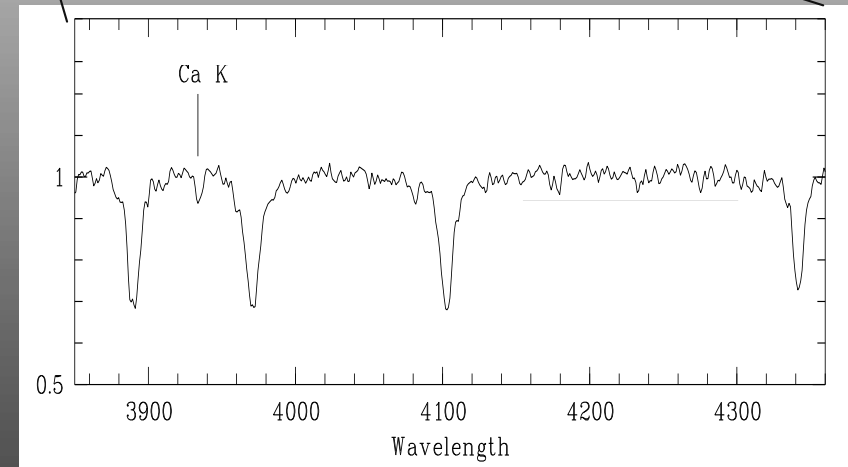
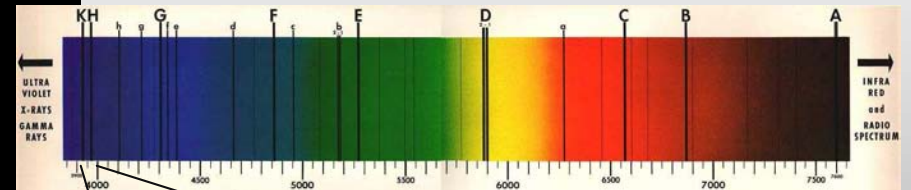
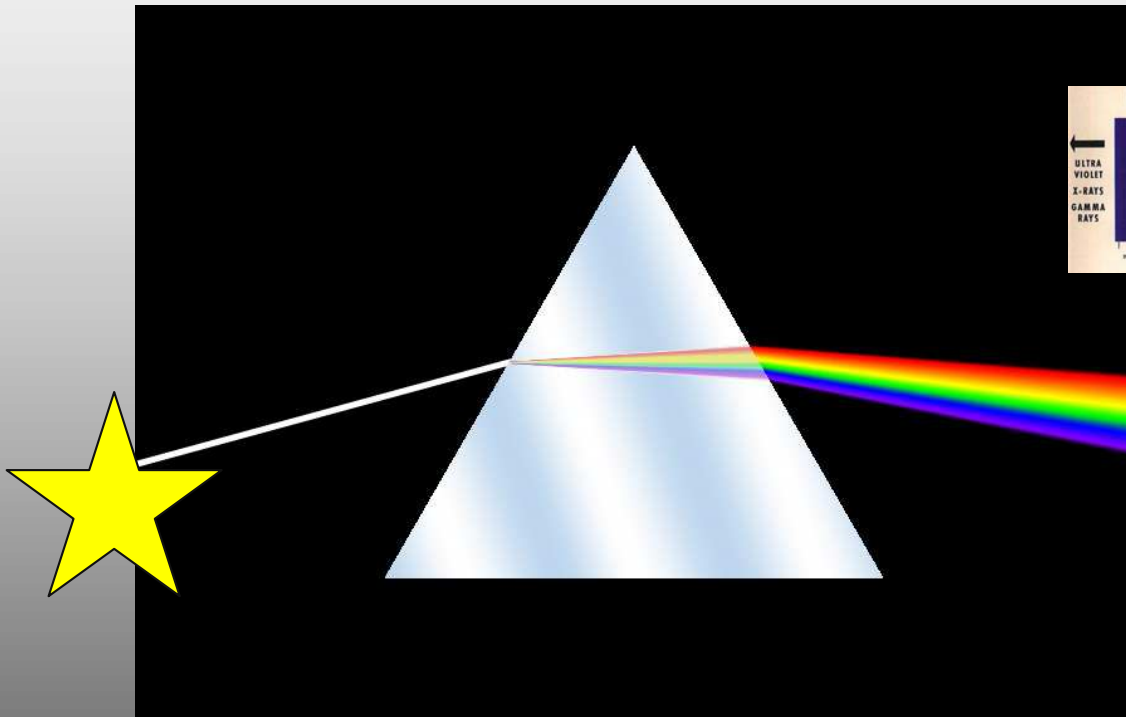
=> **Near-field cosmology**: they connect us to the high-redshift Universe



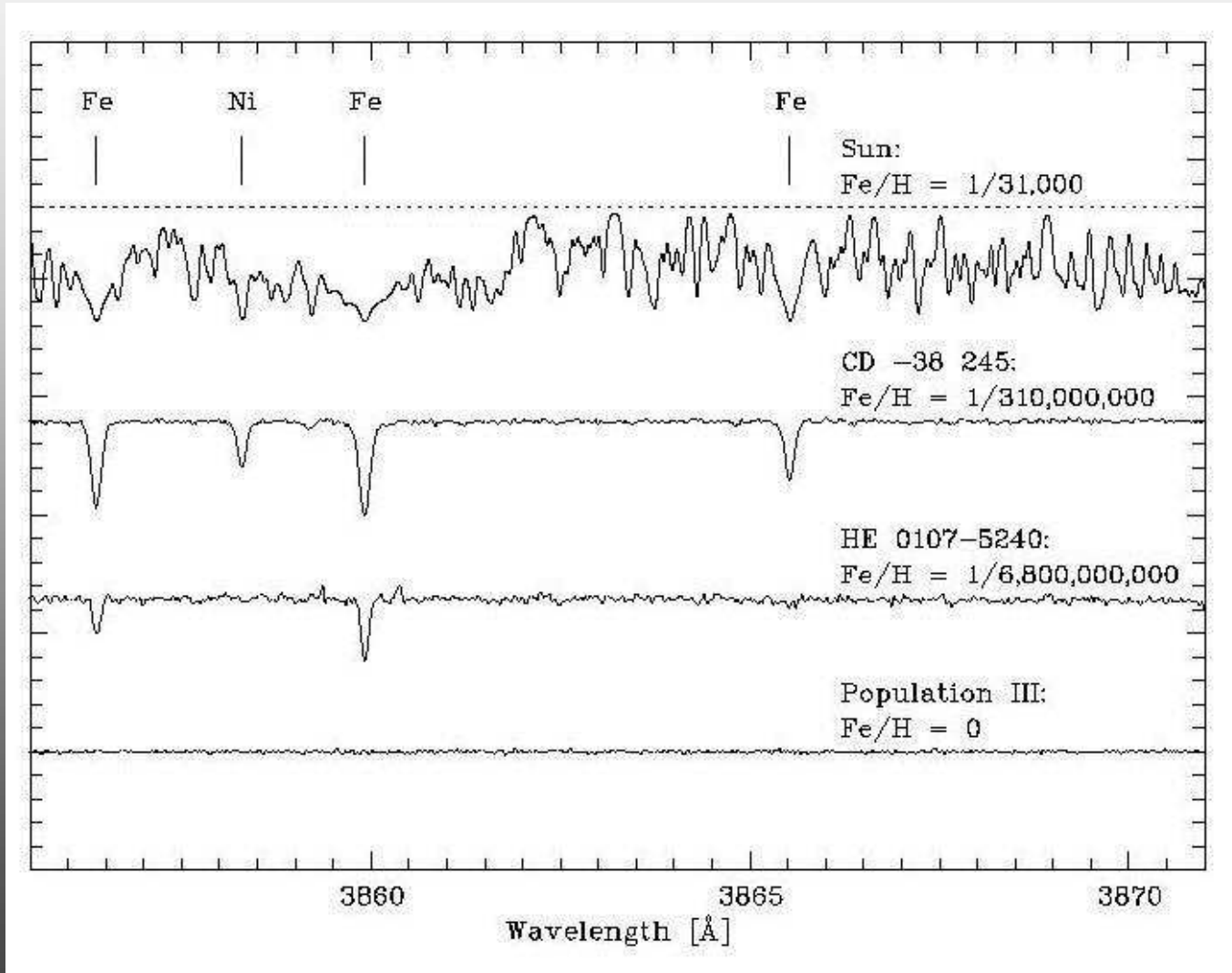




# Making a rainbow



# Spectral Comparison



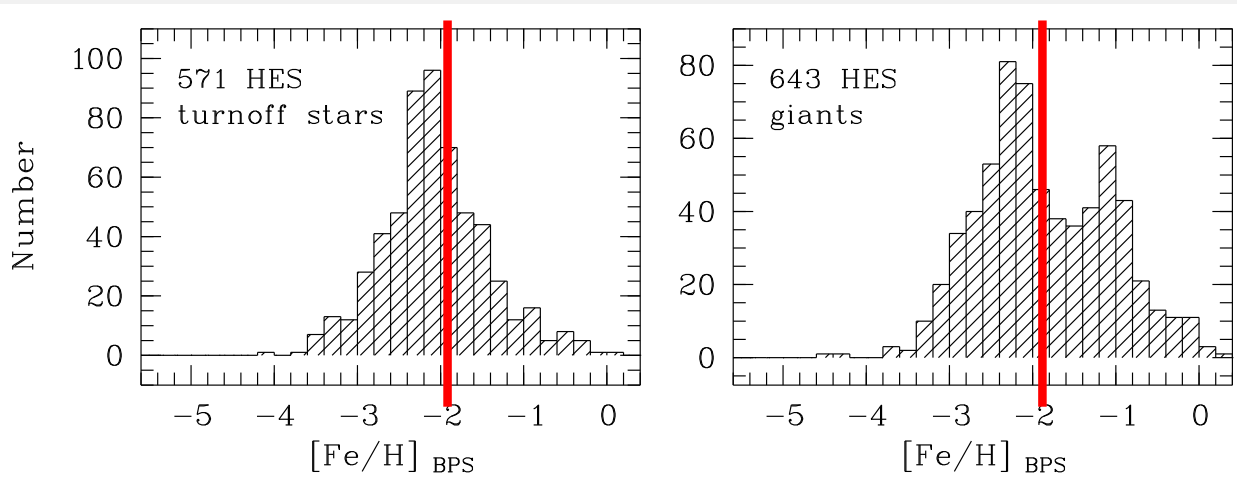
[Fe/H] = 0

[Fe/H] = -4

[Fe/H] = -5.3

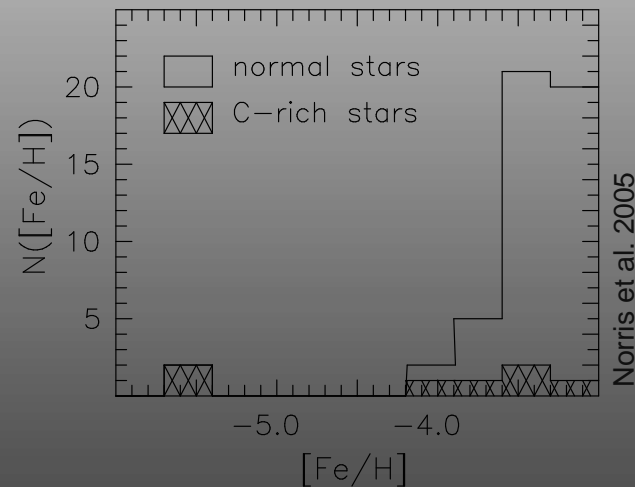
[Fe/H] = -∞

# The Metallicity Distribution Function



Christlieb 2003

Hamburg/ESO survey  
(faint):  
Christlieb and collaborators



Norris et al. 2005

~15 stars with  $[\text{Fe}/\text{H}] < -3.5$

No stars with  $-4 < [\text{Fe}/\text{H}] < -5$

Only two stars with  $[\text{Fe}/\text{H}] < -5.0$

# What [Fe/H] means to me:

Stars with metal contents much less than the Sun

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

[Fe/H] = 0: solar composition

[Fe/H] ~ - 1: boring...

[Fe/H] ~ - 2: good for statistics

[Fe/H] ~ - 3: ... interesting!

[Fe/H] < - 4: Oooh my GOD !!!!!!!!!!! J

# How many metal-poor stars do we know??

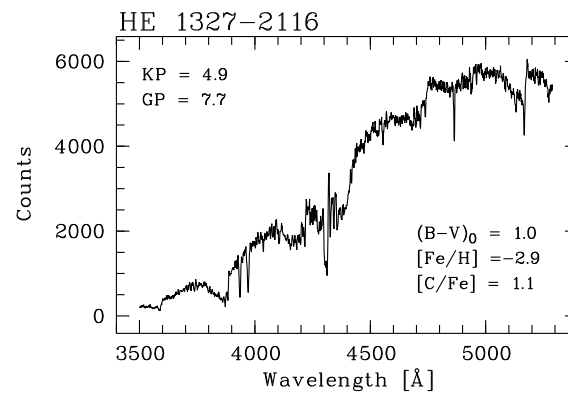
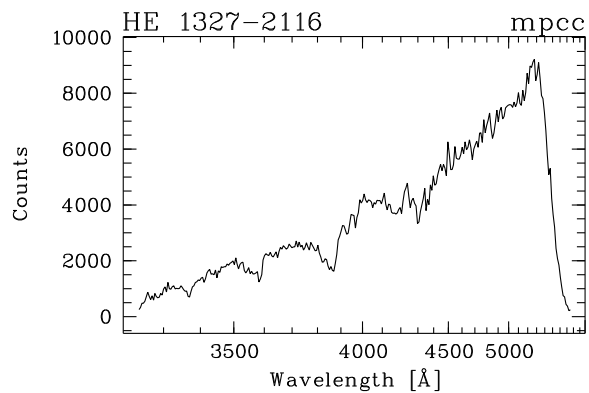
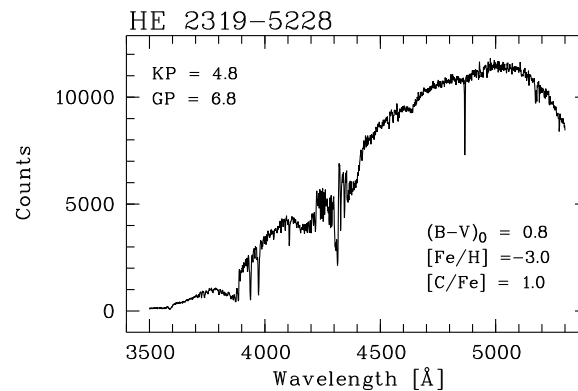
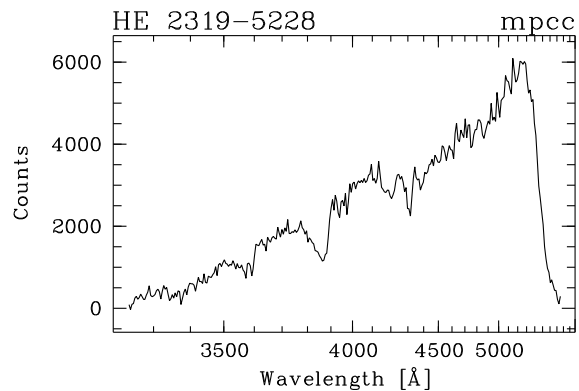
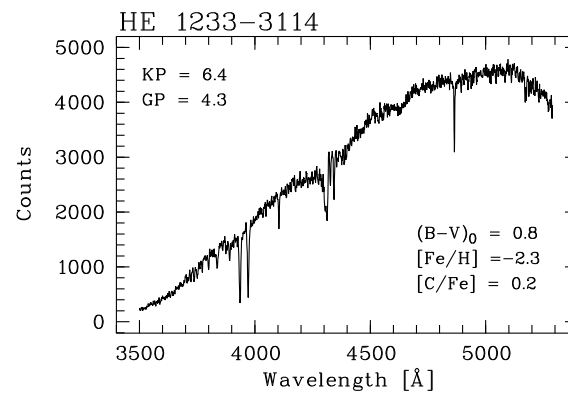
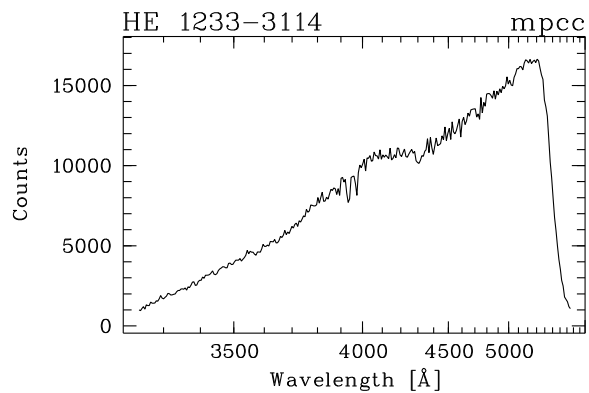
- $-2.0 < [\text{Fe}/\text{H}] < -1.0$ : very many
- $-3.0 < [\text{Fe}/\text{H}] < -2.0$ : many
- $-3.5 < [\text{Fe}/\text{H}] < -3.0$ :  $\sim 300$
- $-4.0 < [\text{Fe}/\text{H}] < -3.5$ :  $\sim 15$
- $-5.0 < [\text{Fe}/\text{H}] < -4.0$ : 1 (yet unpublished)
- $-6.0 < [\text{Fe}/\text{H}] < -5.0$ : 2 ...

# All those elements...

- The Elements Song  
by Tom Lehrer

<http://louhi.kempele.fi/~skyostil/archive/dump/flash/elements.swf>

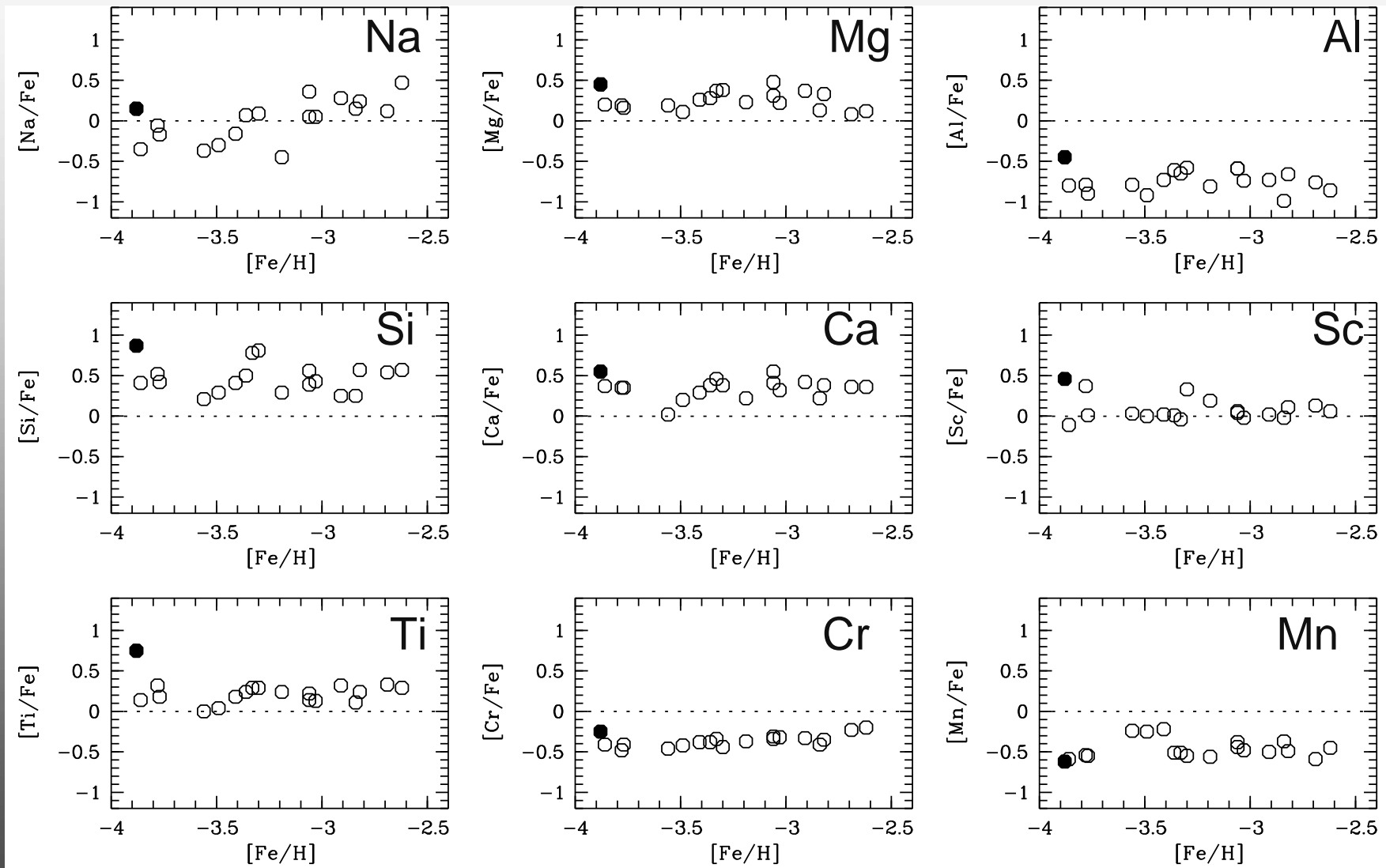
<http://www.edu/cyberpg.com/IEC/elementsong.html>



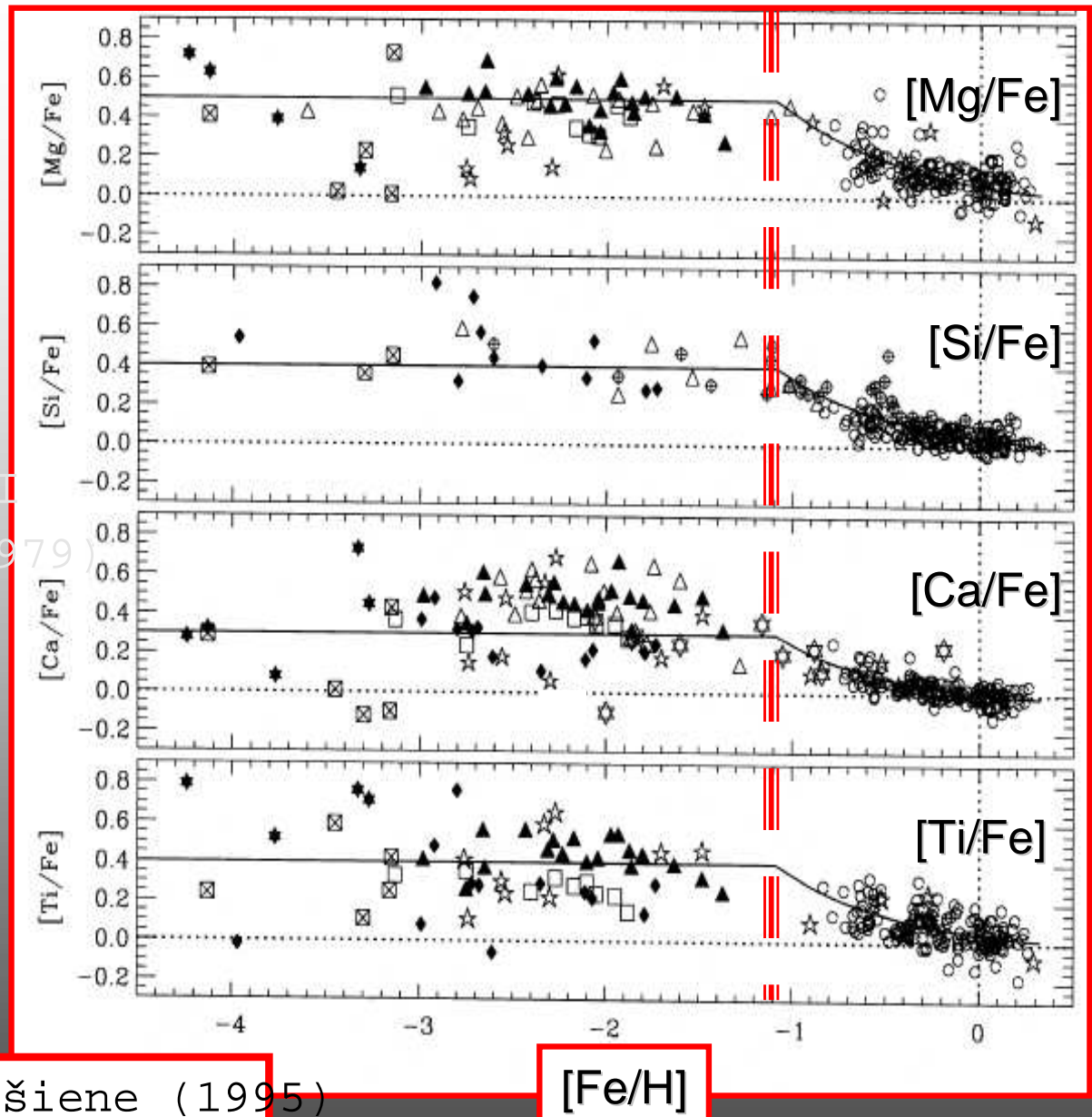
Frebel et al. 2006, ApJ



# “Normal” Metal-Poor Stars



Standard picture:  
iron-rich ejecta  
from SNe Ia  
super-posed on  
pre-existing  
material  
(e.g.  $\alpha$ -elements)  
produced in SNe II  
(see e.g. Tinsley 1979)



Pagel & Tautvaišiene (1995)

$[Fe/H]$

<- more pristine ~ older

# r-Process Element Enhanced Stars

(rapid neutron-capture process)

- Responsible for the production of heavy elements
- Only ~12 stars known that display strong neutron-capture lines associated with the r-process
- Chemical “fingerprint” of one previous nucleosynthesis event
- Nucleo-chronometry: age measurements from radioactive elements Th, U and stable r-process elements (Eu, Os, Ir)

# Heavy neutron-capture elements in stars

	alkali metals I A										alkaline earth metals II A										nonmetals					noble gases 0
Period 1	1																2									
	<b>H</b>																<b>He</b>									
	1.01																4.00									
	Hydrogen																Helium									
Period 2	3	4																10								
	<b>Li</b>	<b>Be</b>																<b>Ne</b>								
	6.94	9.01																20.18								
	Lithium	Beryllium																Neon								
Period 3	11	12																18								
	<b>Na</b>	<b>Mg</b>																<b>Ar</b>								
	22.99	24.31																39.95								
	Sodium	Magnesium																Argon								
	transition metals																									
			III B	IV B	V B	VI B	VII B	VIII			IB	II B														
Period 4	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36								
	<b>K</b>	<b>Ca</b>	<b>Sc</b>	<b>Ti</b>	<b>V</b>	<b>Cr</b>	<b>Mn</b>	<b>Fe</b>	<b>Co</b>	<b>Ni</b>	<b>Cu</b>	<b>Zn</b>	<b>Ga</b>	<b>Ge</b>	<b>As</b>	<b>Se</b>	<b>Br</b>	<b>Kr</b>								
	39.10	40.08	44.96	47.88	50.94	52.00	54.95	55.85	58.93	58.70	63.55	65.39	69.72	72.61	74.92	78.96	79.90	83.80								
	Potassium	Calcium	Scandium	Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper	Zinc	Gallium	Germanium	Arsenic	Selenium	Bromine	Krypton								
Period 5	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54								
	<b>Rb</b>	<b>Sr</b>	<b>Y</b>	<b>Zr</b>	<b>Nb</b>	<b>Mo</b>	<b>Tc</b>	<b>Ru</b>	<b>Rh</b>	<b>Pd</b>	<b>Ag</b>	<b>Cd</b>	<b>In</b>	<b>Sn</b>	<b>Sb</b>	<b>Te</b>	<b>I</b>	<b>Xe</b>								
	85.47	87.62	88.91	91.22	92.91	95.94	(98)	101.07	102.91	106.4	107.87	112.41	114.82	118.71	121.74	127.60	126.90	131.29								
	Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum	(Technetium)	Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	Iodine	Xenon								
Period 6	55	56	Lanthanide series (see below)	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86								
	<b>Cs</b>	<b>Ba</b>		<b>Hf</b>	<b>Ta</b>	<b>W</b>	<b>Re</b>	<b>Os</b>	<b>Ir</b>	<b>Pt</b>	<b>Au</b>	<b>Hg</b>	<b>Tl</b>	<b>Pb</b>	<b>Bi</b>	<b>Po</b>	<b>At</b>	<b>Rn</b>								
	132.91	137.33		178.49	180.94	183.85	186.21	190.23	192.22	195.08	196.97	200.59	204.38	207.2	208.98	(209)	(210)	(222)								
	Cesium	Barium		Hafnium	Tantalum	Tungsten	Rhenium	Osmium	Iridium	Platinum	Gold	Mercury	Thallium	Lead	Bismuth	Polonium	Astatine	Radon								
Period 7	87	88	Actinide series (see below)	104	105	106	107	108	109	110	111	112		114		116		118								
	<b>Fr</b>	<b>Ra</b>		<b>Rf</b>	<b>Db</b>	<b>Sg</b>	<b>Bh</b>	<b>Hs</b>	<b>Mt</b>																	
	(223)	226.03		(261)	(262)	(263)	(262)	(265)	(266)	(269)	(272)	(277)		(281)		(289)		(293)								
	Francium	Radium		Rutherfordium	Dubnium	Seaborgium	Berkelium	Hassium	Moscovium	(Tennessine)	(Oganesson)	(Bohrium)		(Tennessine)		(Oganesson)		(Tennessine)								

rare earth elements—Lanthanide series

57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
<b>La</b>	<b>Ce</b>	<b>Pr</b>	<b>Nd</b>	<b>Pm</b>	<b>Sm</b>	<b>Eu</b>	<b>Gd</b>	<b>Tb</b>	<b>Dy</b>	<b>Ho</b>	<b>Er</b>	<b>Tm</b>	<b>Yb</b>	<b>Lu</b>
138.91	140.12	140.91	144.24	(145)	150.4	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04	174.97
Lanthanum	Cerium	Praseodymium	Niodymium	(Promethium)	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium

Actinide series

89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
<b>Ac</b>	<b>Th</b>	<b>Pa</b>	<b>U</b>	<b>Np</b>	<b>Pu</b>	<b>Am</b>	<b>Cm</b>	<b>Bk</b>	<b>Cf</b>	<b>Es</b>	<b>Fm</b>	<b>Md</b>	<b>No</b>	<b>Lr</b>
227.03	232.04	231.04	238.03	237.05	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(260)
Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium

HE 1523-0901

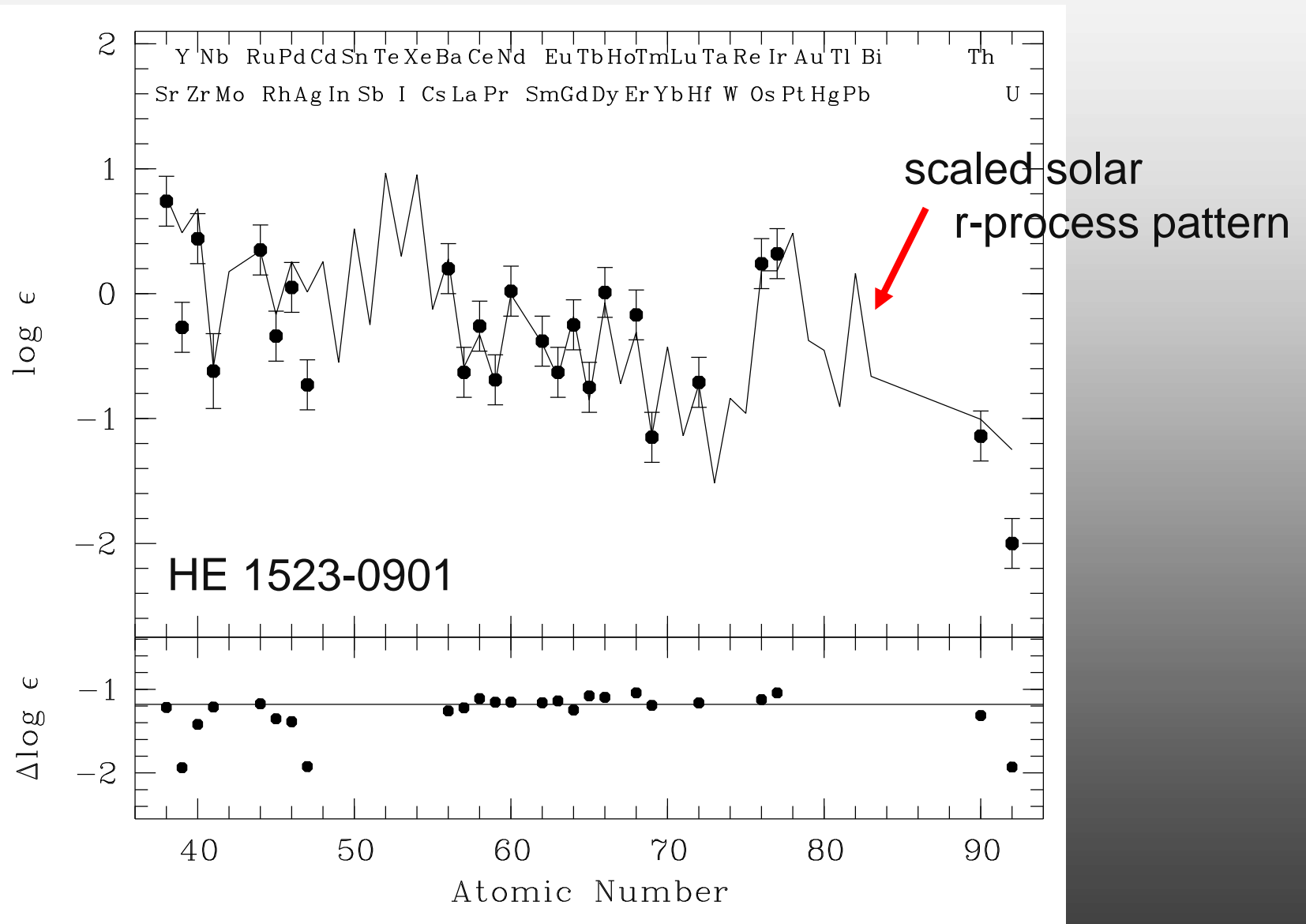


# 5. HE 1523–0901

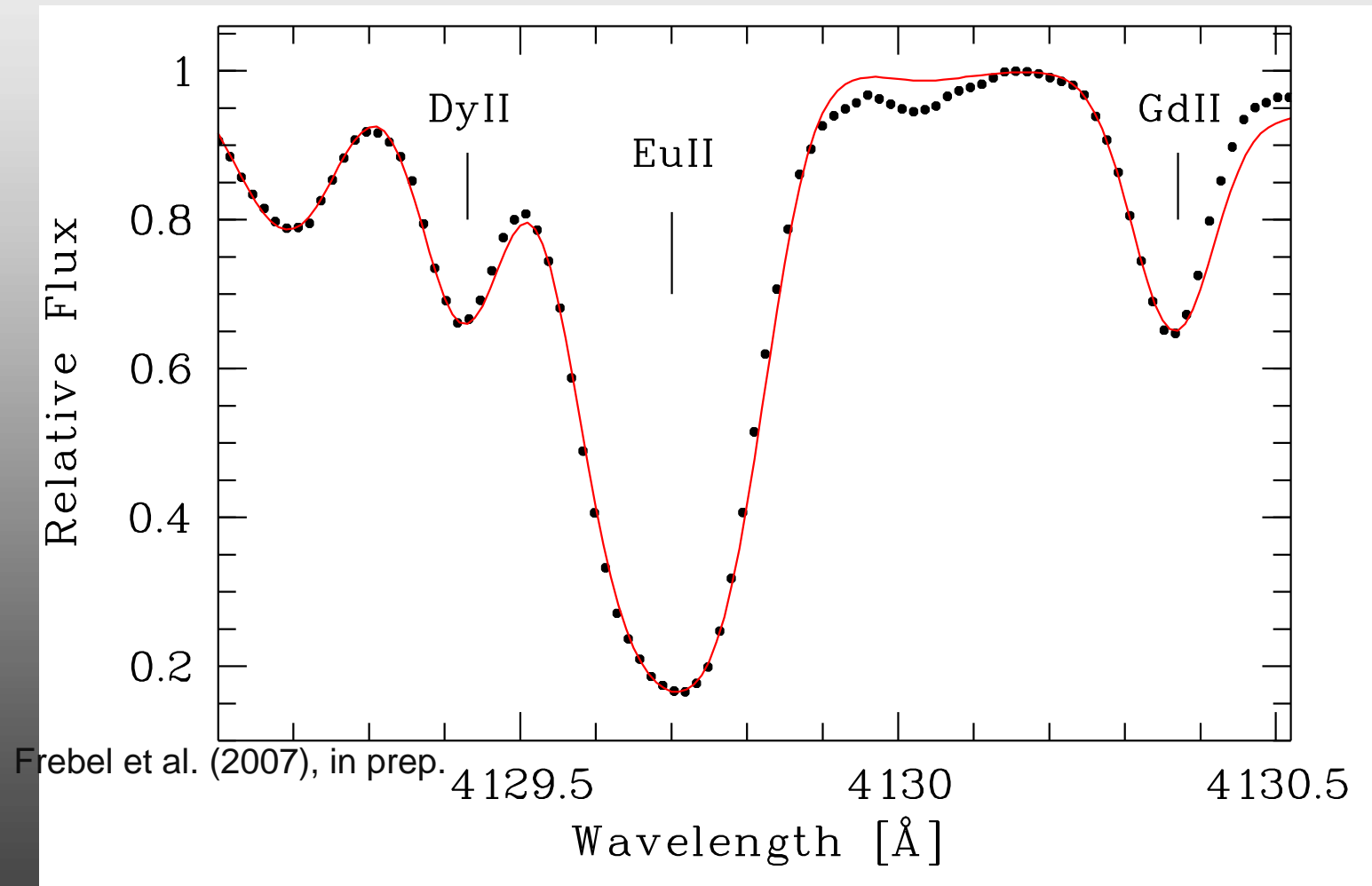
Basic and stellar parameters:

- Magnitude:  $B = 12.1$  mag
- Colour:  $(B-V)_0 = 0.70$  mag
- Reddening:  $E(B-V) = 0.02$
  
- *BVRIJHK* photometry:  $T_{\text{eff}} = 4630 \pm 70\text{K}$  (on Alonso et al. 1996 scale)
- Surface gravity:  $\log g = 1.0$  (ionisation equilibrium)  
=> red giant
- Metallicity:  $[\text{Fe}/\text{H}] = -3.0$

# The r-Process Pattern

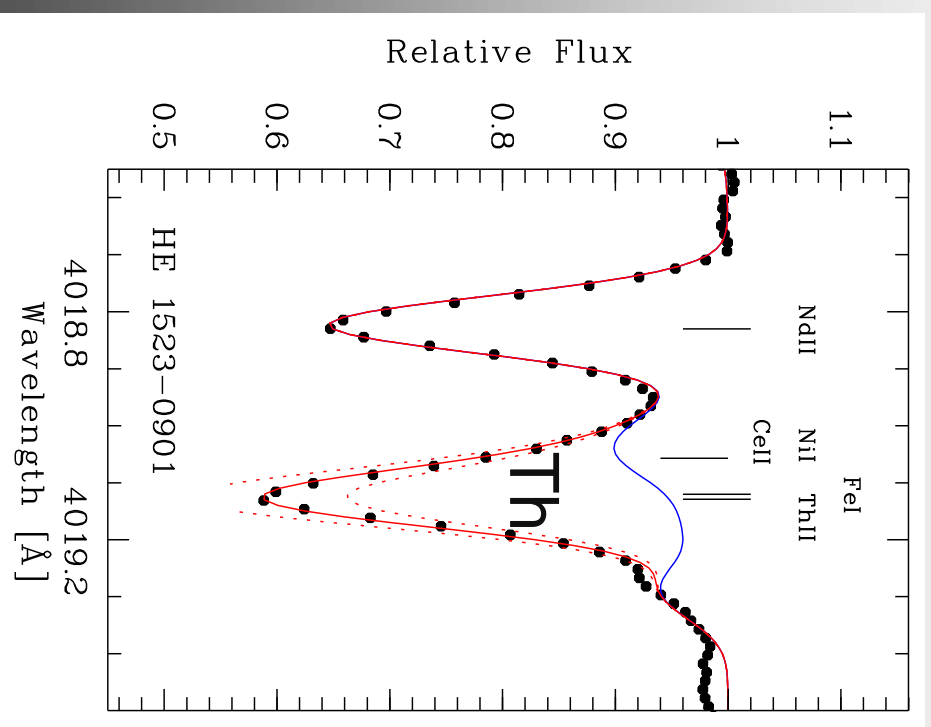


# Abundances of HE 1523-0901



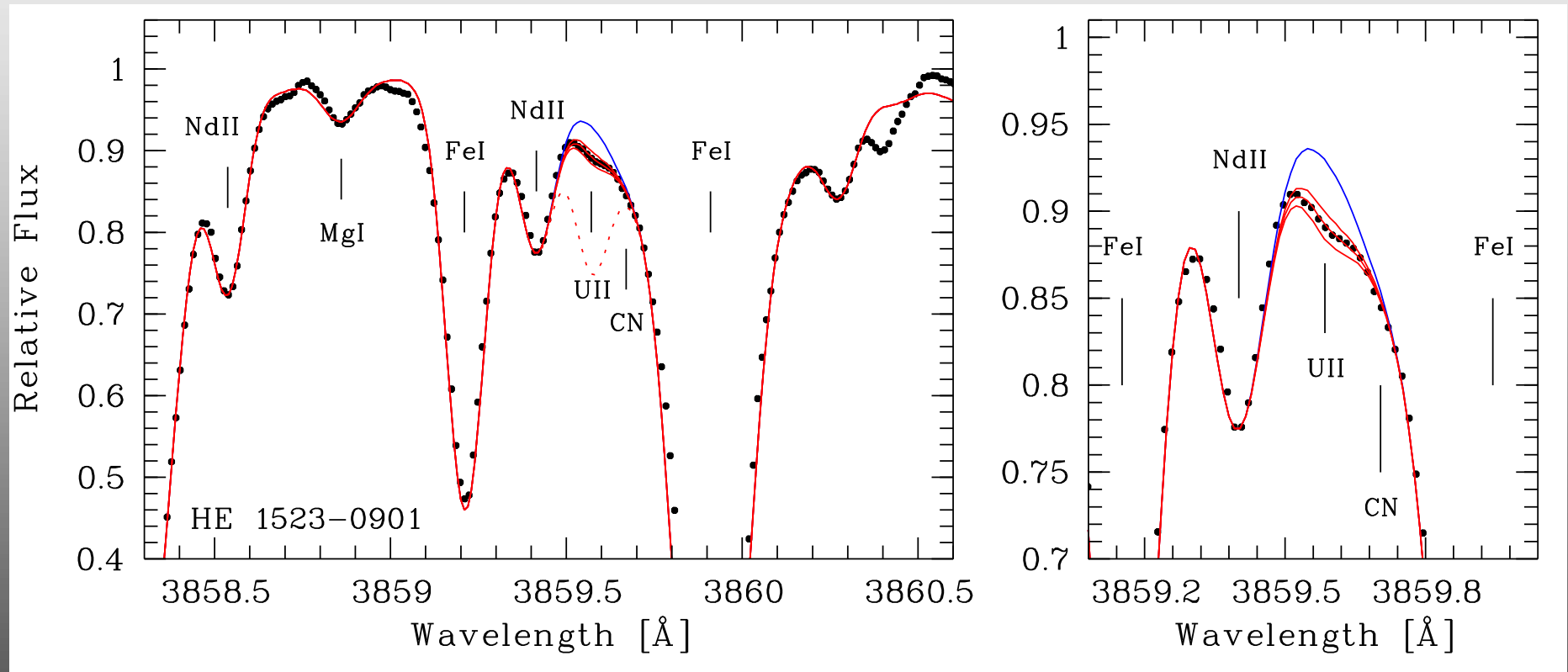


# Th II Line 4019Å



Frebel et al. (2007), in prep.

# U II at 3859Å



Frebel et al. (2007), ApJL in press

# Nucleo-Chronometric Age Dating

Age estimates can be obtained from a comparison of an 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.

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

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

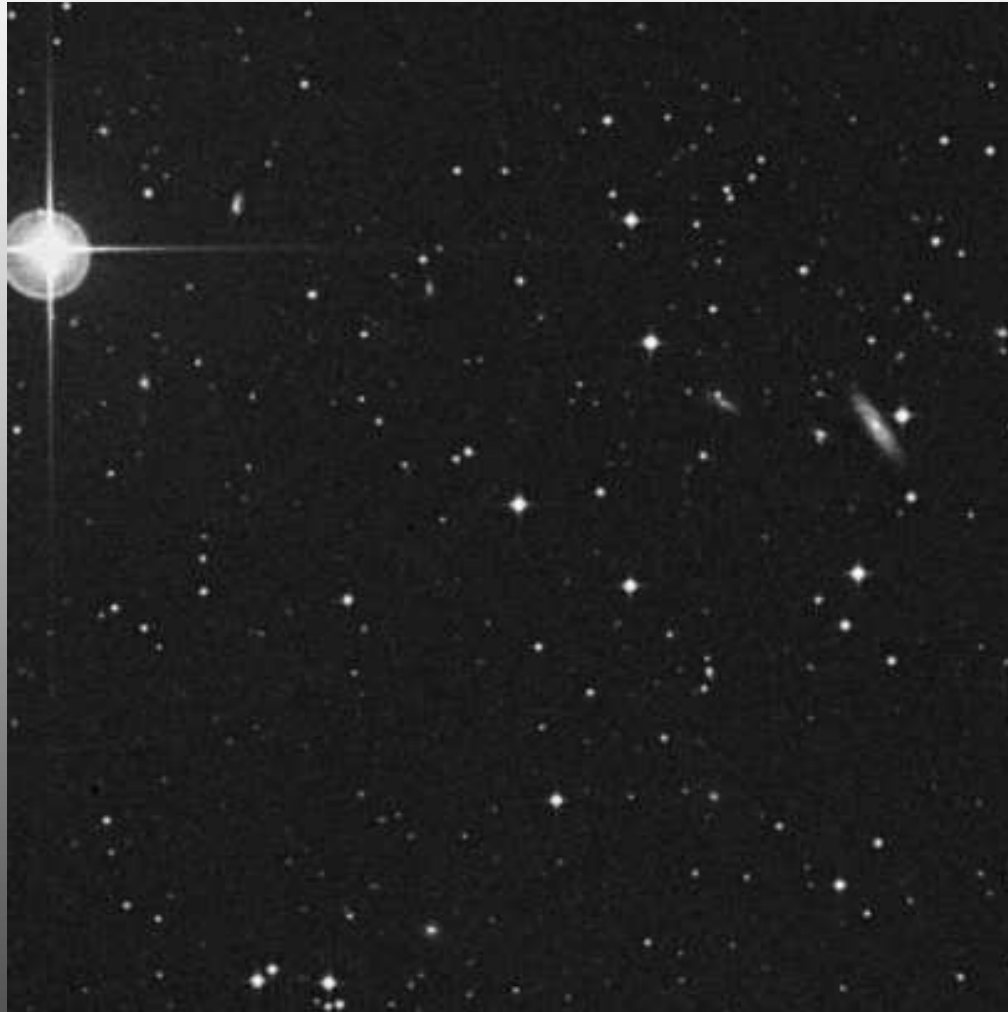
$$\Delta t = 21.8 * (\log (\text{U}/\text{Th})_0 - \log (\text{U}/\text{Th})_{\text{obs}})$$

# The Age of HE 1523-0901

Ratio	Age
Th/Eu	11.5 $\pm$ 4.7
Th/Os	10.7 $\pm$ 4.7
Th/Ir	15.0 $\pm$ 4.7
U/Eu	13.2 $\pm$ 2.2
U/Os	12.9 $\pm$ 2.2
U/Ir	14.1 $\pm$ 2.2
U/Th	13.0 $\pm$ 3.3
Age of HE 1523-0901: <b>average</b>	<b>13.2<math>\pm</math>1.1<math>\pm</math>2.0 Gyr</b>

Age of the Universe: 13.7 Gyr (from WMAP, Spergel et al. 06)

# HE 1327-2326

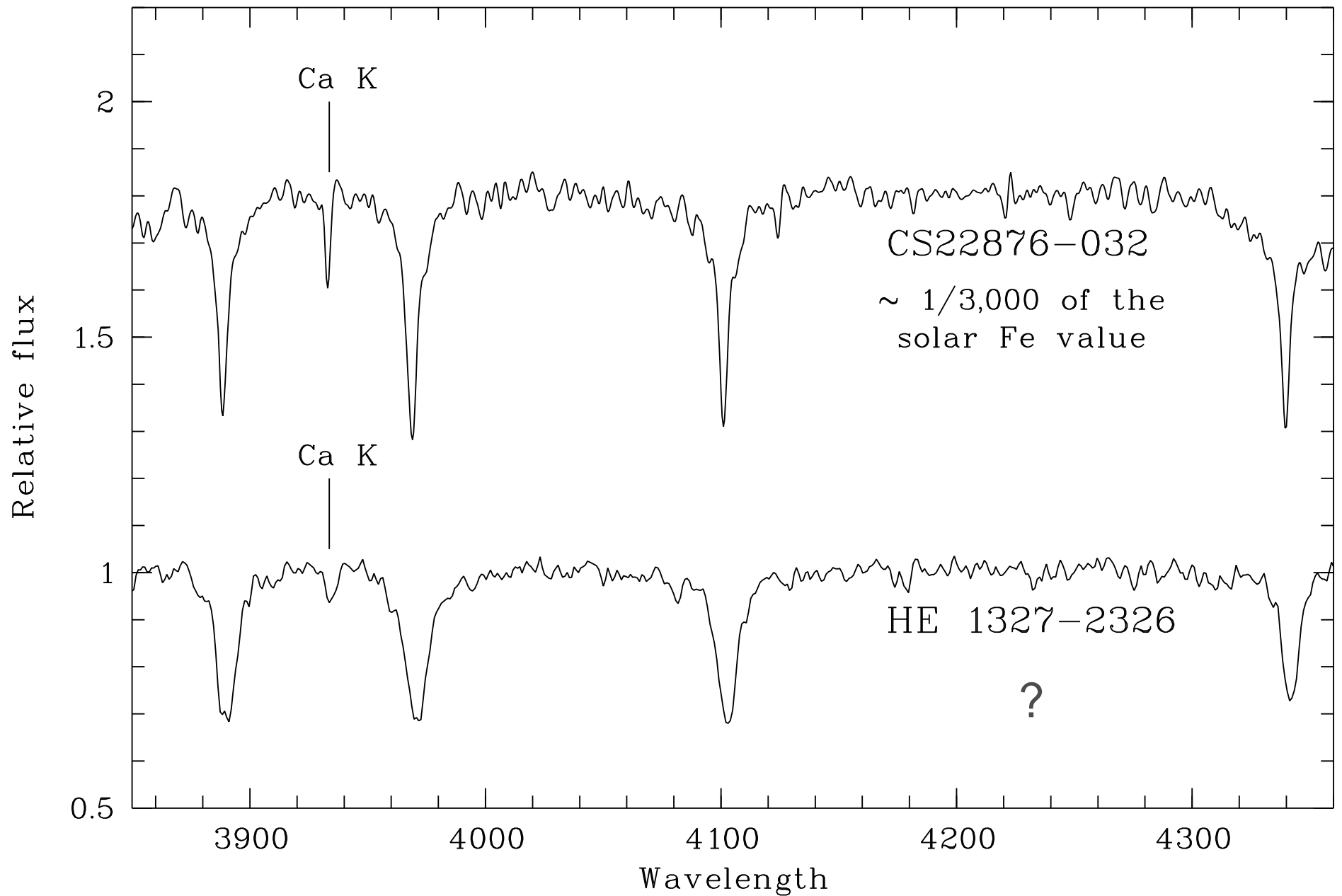


# 3. HE 1327–2326

## Basic and stellar parameters:

- Magnitude:  $B = 14.016$  mag
- Colour:  $(B-V)_0 = 0.40$  mag
- Reddening:  $E(B-V) = 0.06 - 0.096$
  
- *BVR*K photometry:  $T_{\text{eff}} = 6180 \pm 80\text{K}$  (on Alonso et al. 1996 scale)
- Proper motion is  $\mu = 0.0733$  arcsec/yr  
=>  $M_V > 3.2$   
=> surface gravity:  $\log g = 3.7$  or  $4.5$  (subgiant or dwarf)
- Metallicity:  $[\text{Fe}/\text{H}] = -5.4$

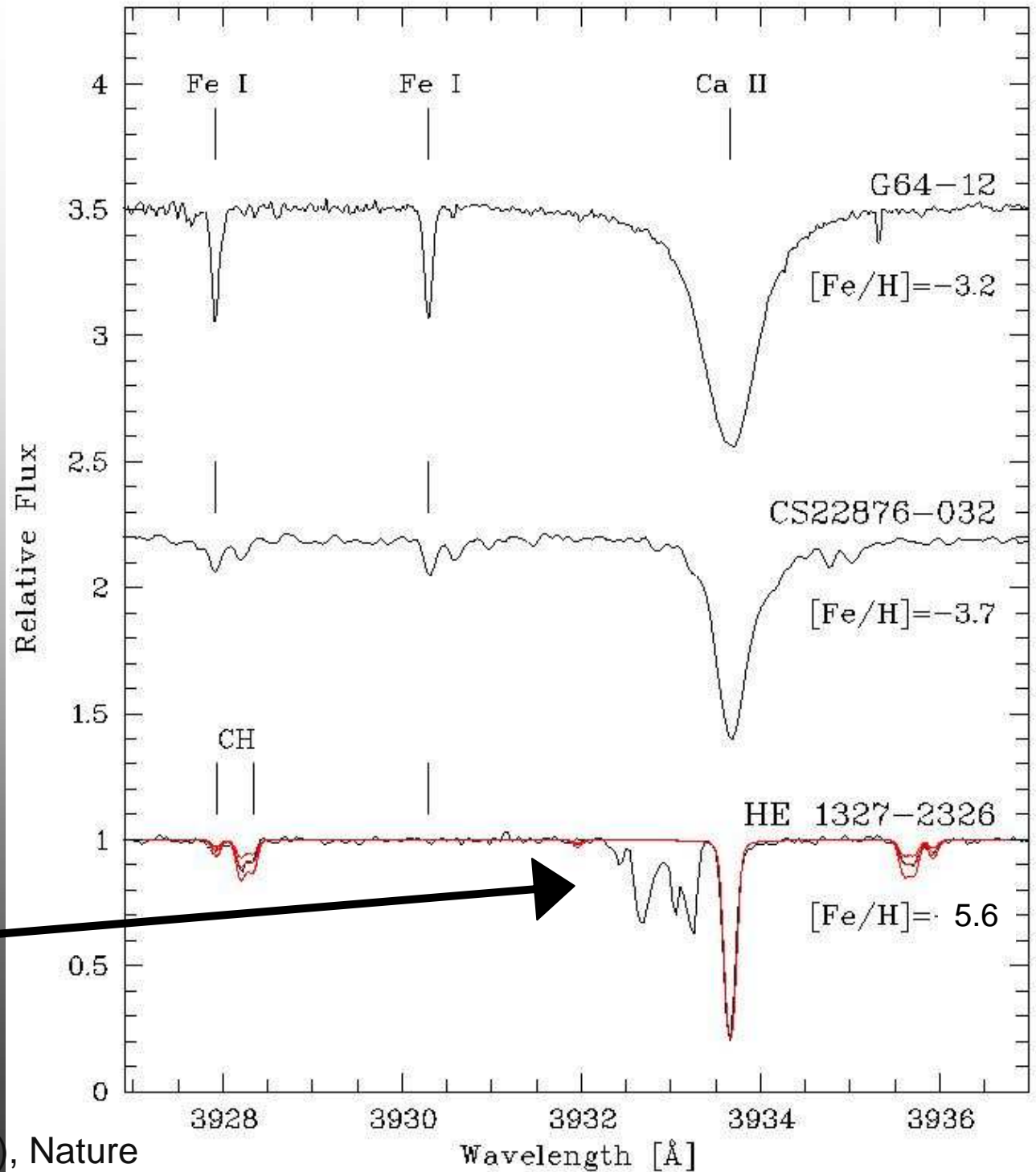
# Medium-resolution spectrum



# Ca K line

High-resolution  
Subaru/HDS  
spectra

Interstellar Ca



Frebel et al. (2005), Nature

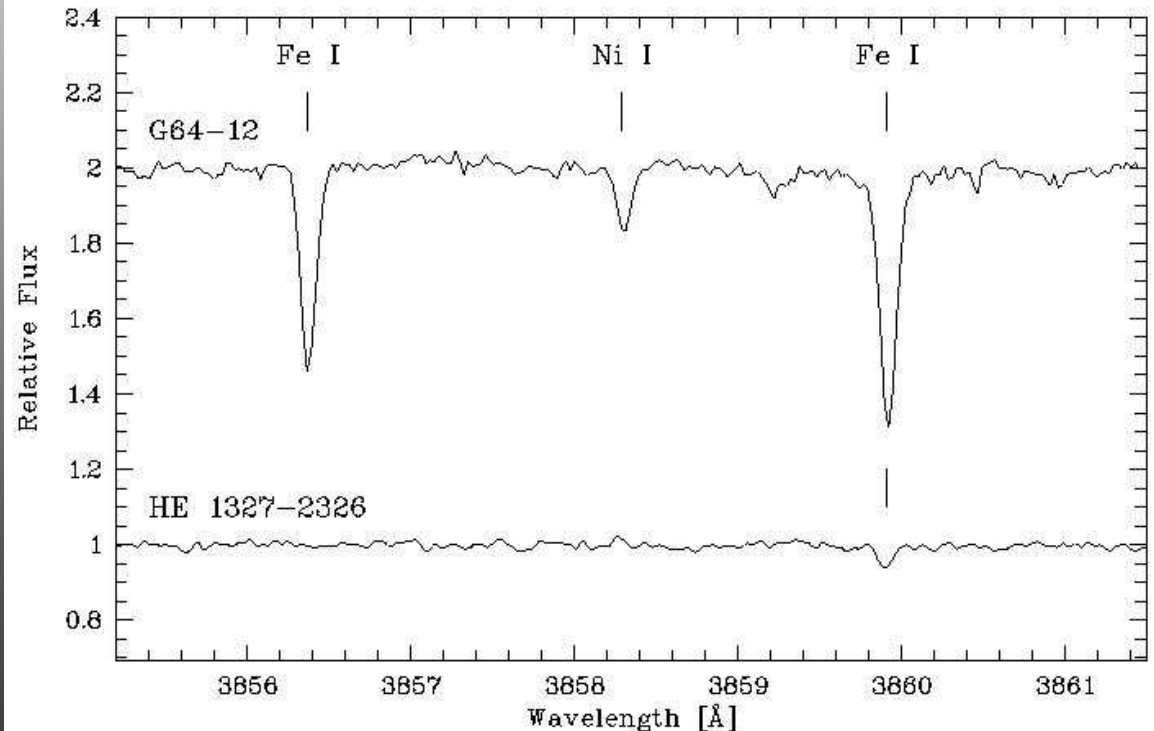
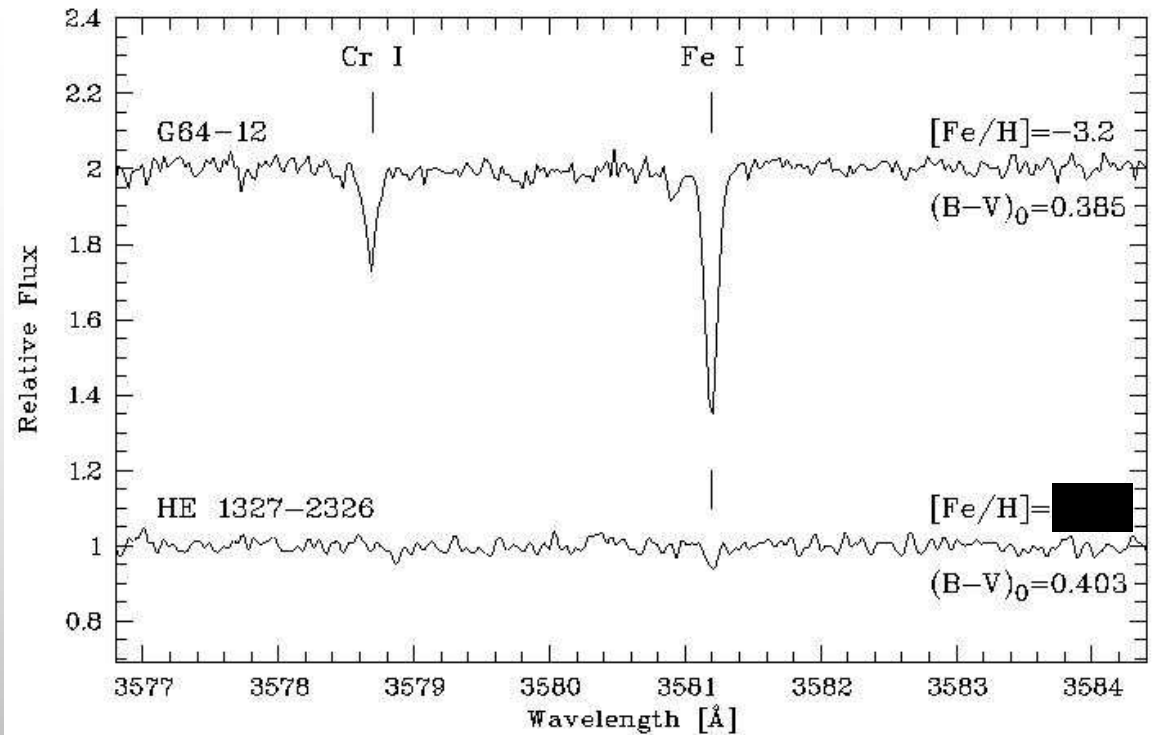


# Fe I Lines

The lowest iron abundance ever measured in a star:

$$[\text{Fe}/\text{H}] = -5.4$$

This number corresponds to 1/250,000 of the solar iron content!!

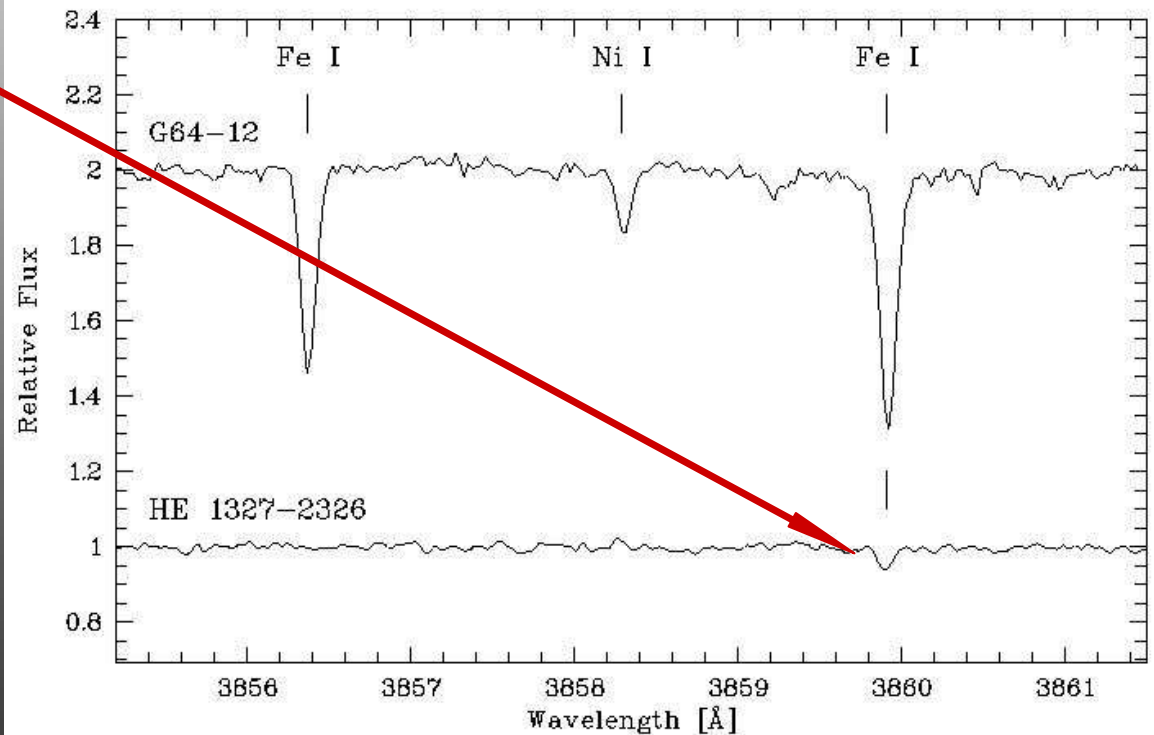
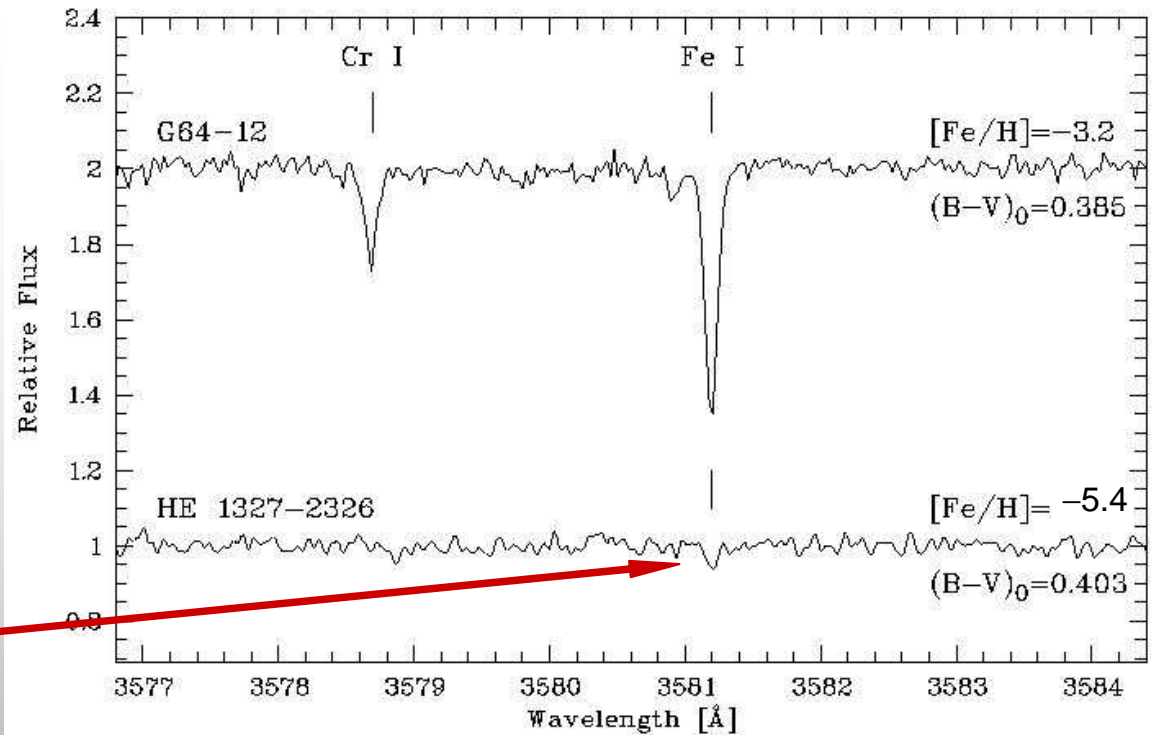


# Fe I Lines

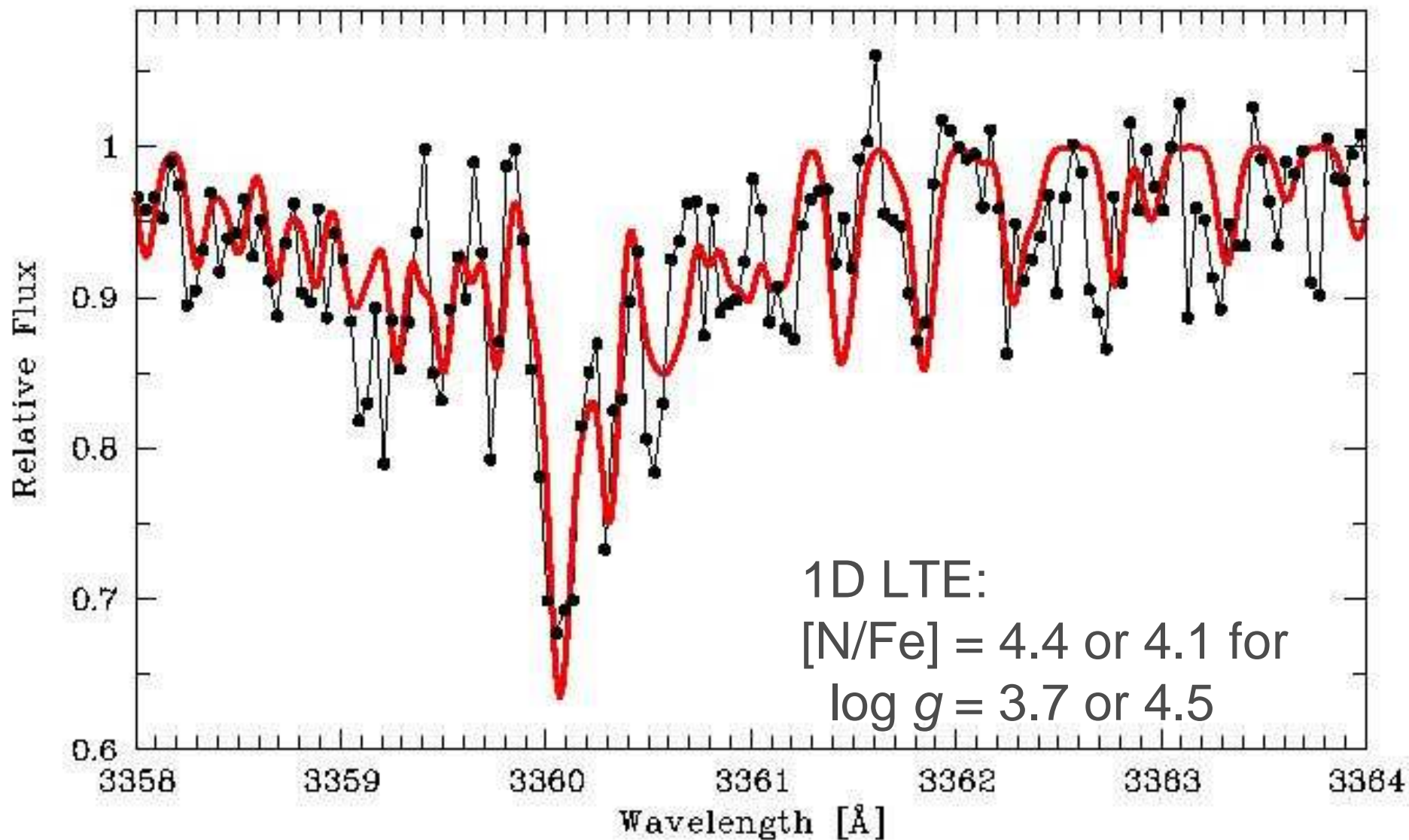
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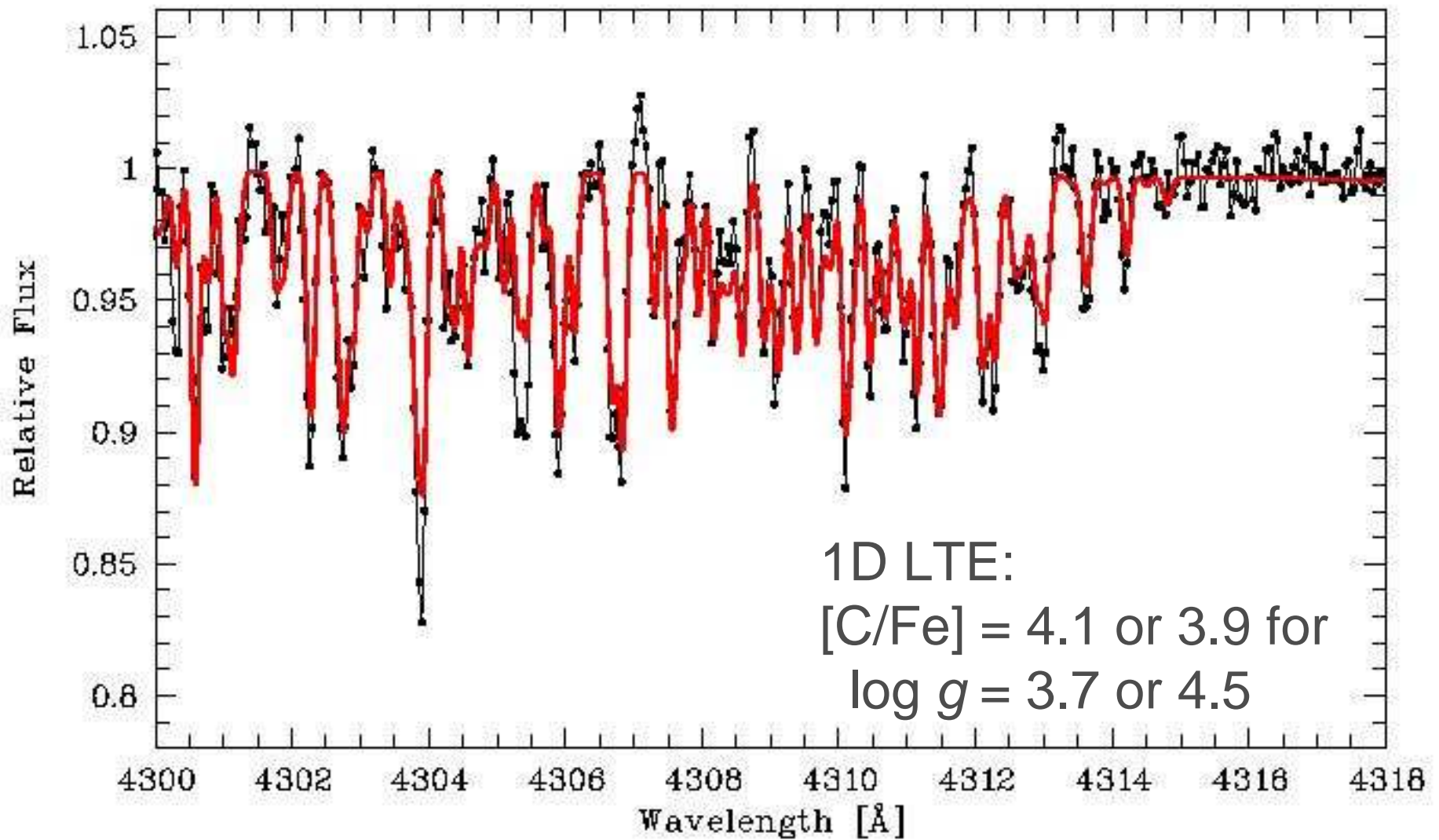
This number corresponds to 1/250,000 of the solar iron content!!



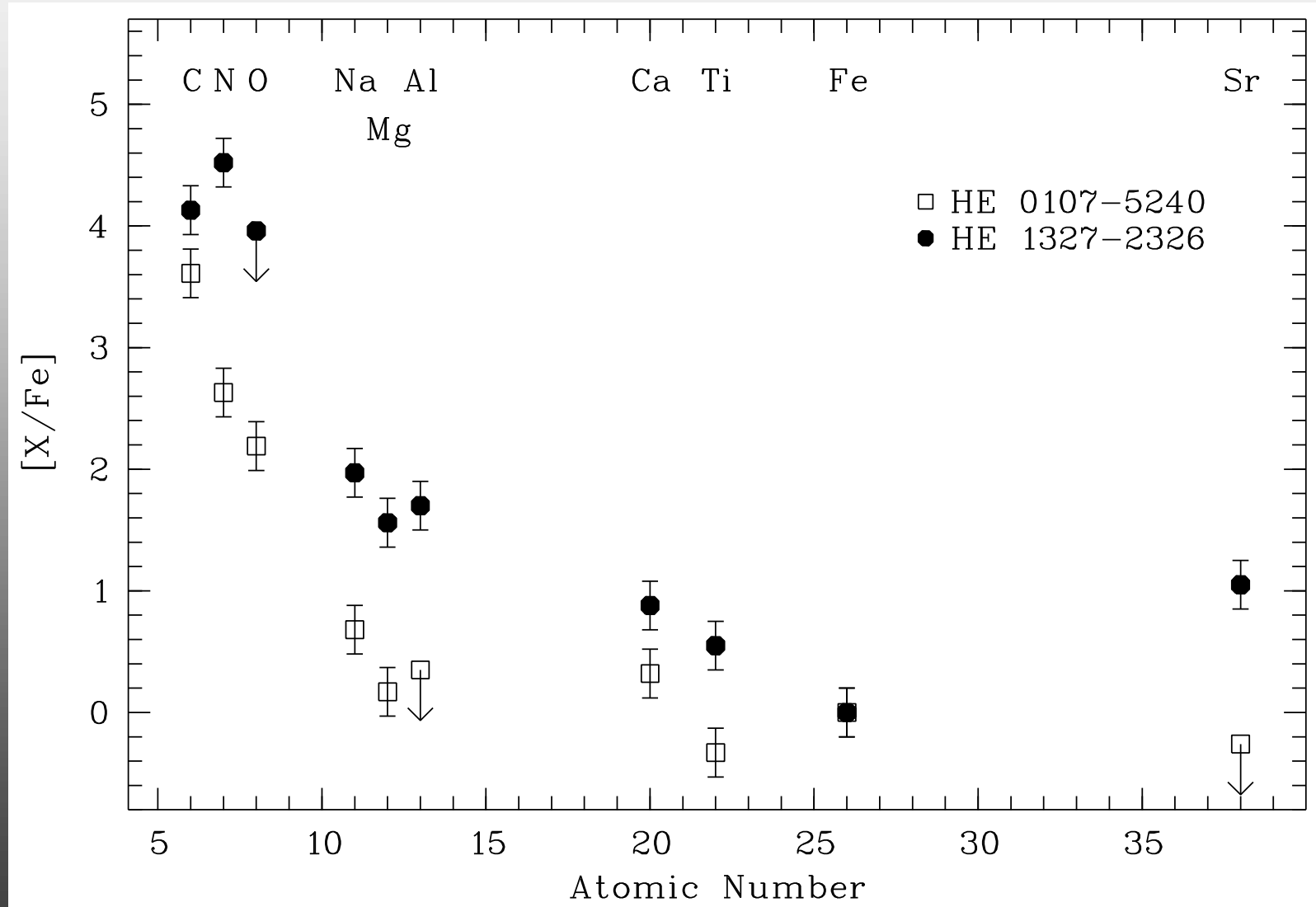
# NH 3360



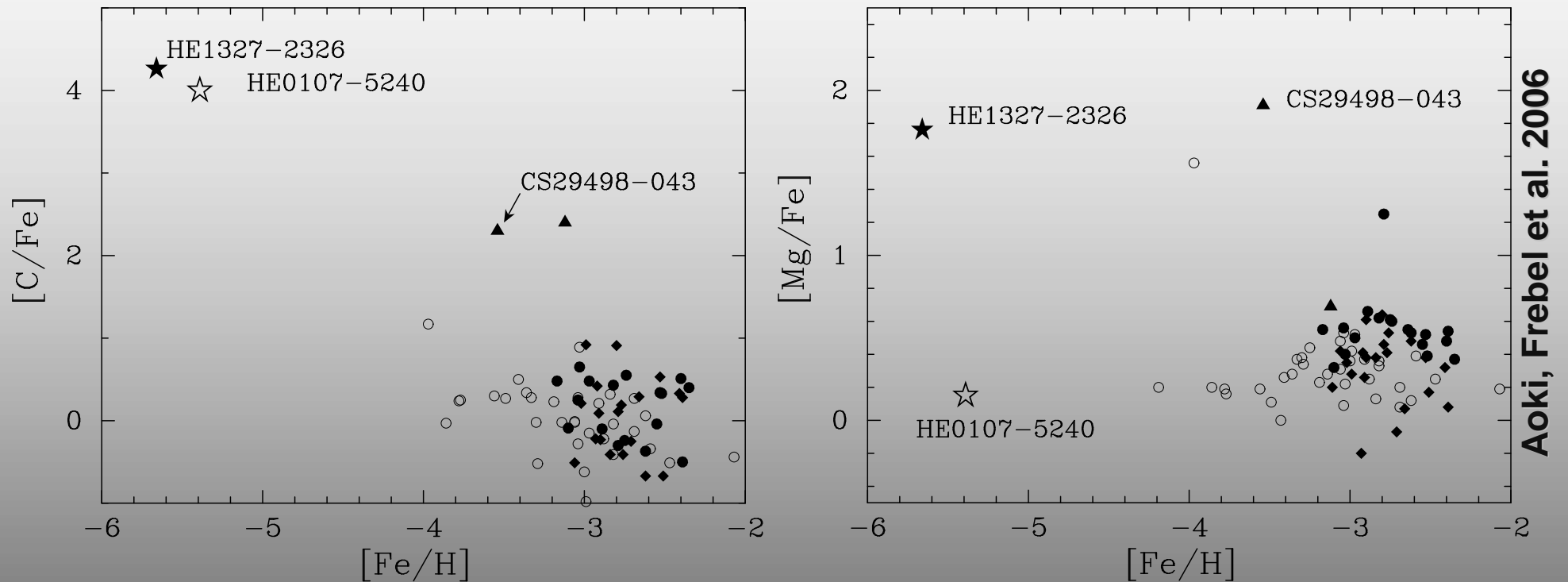
# CH 4300 Bandhead



# The abundance patterns of HE 1327–2327 and HE 0107–5240



# What is so Special About HE 1327–2326?



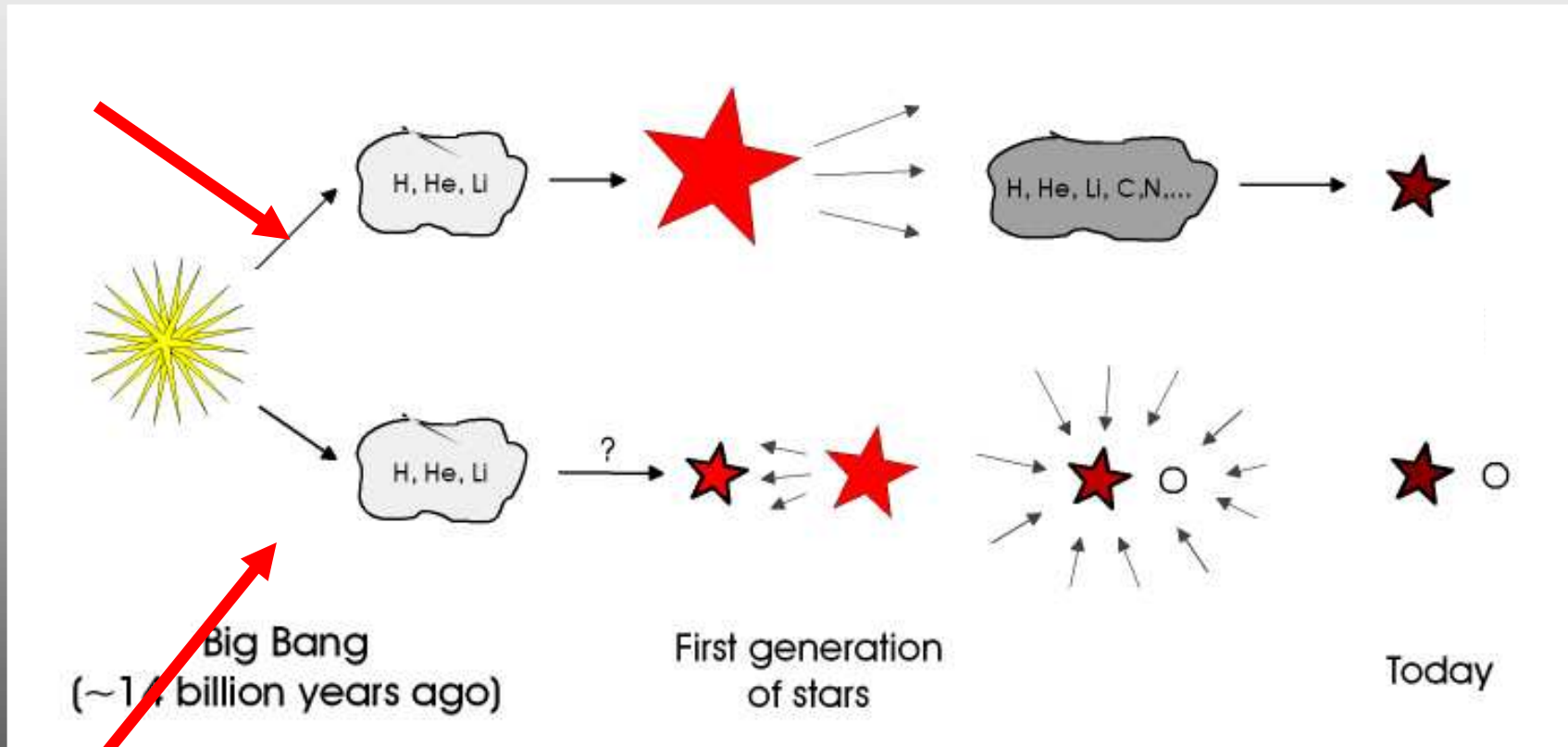
Aoki, Frebel et al. 2006

HE 1327–2326 has a very different chemical signature compared with the more metal-rich stars! So does HE 0107–5240 (Christlieb et al. 2002, 2004)

This is crucial observational information for the study of the early Universe

# Possible Scenarios for the Origin of the Abundance Pattern

Pre-enrichment by Pop III SN  $\Rightarrow$  Pop II star



Binary system with mass transfer  $\Rightarrow$  Pop III star

# “Chemical Compositions of the Galactic Halo”

- New program to observe metal-poor stars w/  $[Fe/H] < -2.0$
- Northern hemisphere
- Hobby-Eberly Telescope at McDonald Observatory
- Long-term status: 50+20 hours allocated for UT07-01,  
35 hours for UT07-02

GOAL: observe ~700 stars in ~4 years

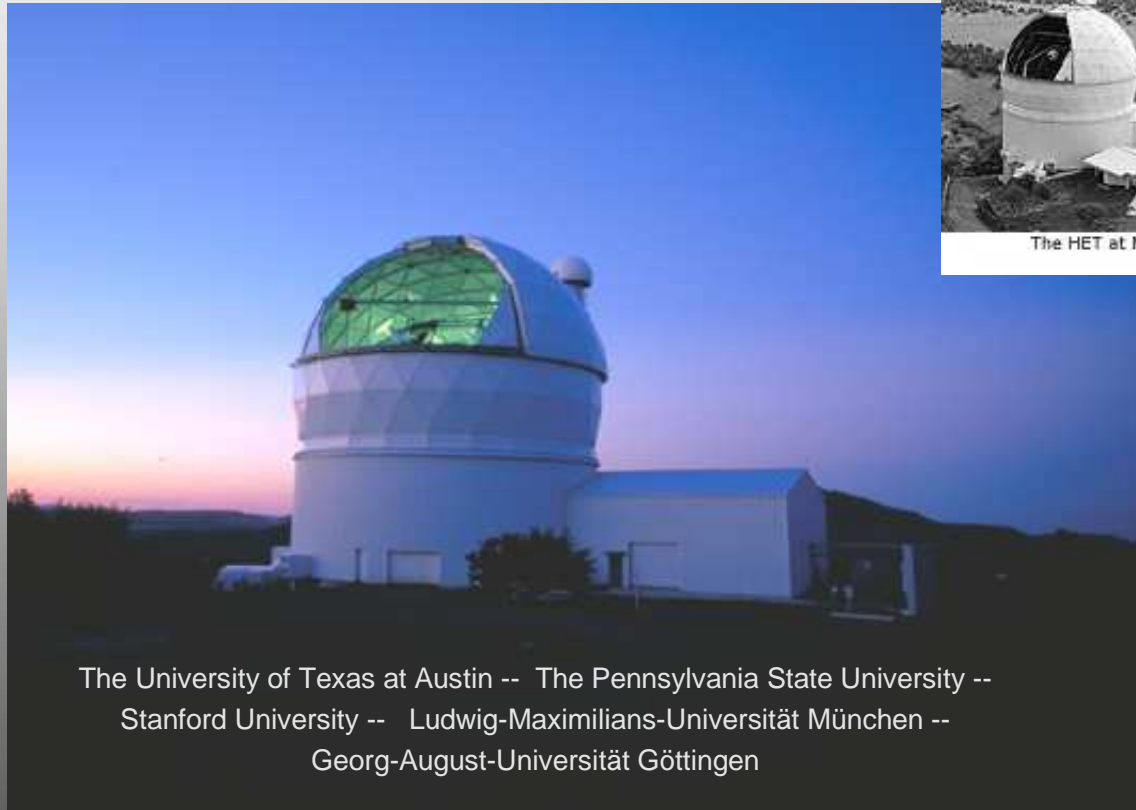
=> largest high-res database so far

The team:

C. Allende Prieto, T. Beers, V. Bromm, J. Cowan, A. Frebel, J. Rhee, I. Roederer, C. Sneden



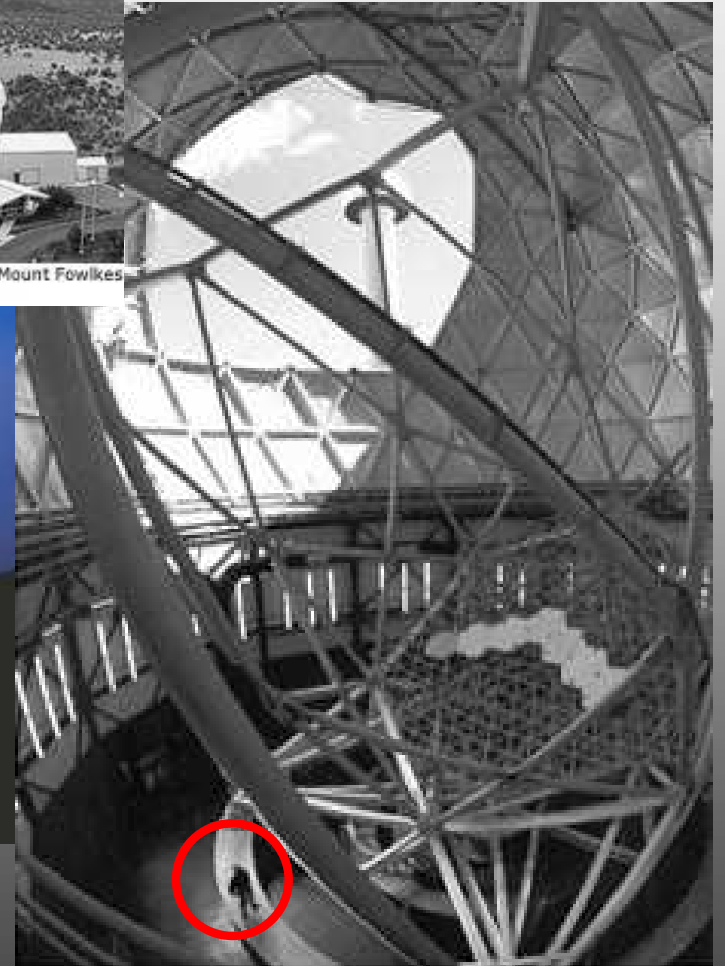
# Hobby-Eberly-Telescope



The University of Texas at Austin -- The Pennsylvania State University --  
Stanford University -- Ludwig-Maximilians-Universität München --  
Georg-August-Universität Göttingen



The HET at Mount Fowlkes



A sense of scale: A man stands next to the HET

# The way I observe...

I get an email in the morning:

```
Date: Tue, 27 Mar 2007 11:38:33 +0000(GMT)
From: Astronomer <astronomer@mcs.as.utexas.edu>
To: anna@astro.as.utexas.edu
Subject: ut...011
```

```
UT Date: 27 Mar 2007
```

```
You have data from the HET.
```

```
target numbers:
```

```
2385 2387 2398 2416 2383
```

```
...
```

# What can we do with all those data??

- r-process rich: high Eu; s-process: high Ba, low Eu
- alpha-poor: low Ca
- C-rich stars
- $[\text{Fe}/\text{H}] < -4$  stars
- anything peculiar
  
- Statistical analyses, CEMP-frequencies, spatial distribution
- Metallicity distribution function
- More global chemical characteristics of the Galactic components
  
- Testing theoretical predictions
  
- ... and more!