# The quest for the most metal-poor stars: From ongoing to future surveys

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# Overview

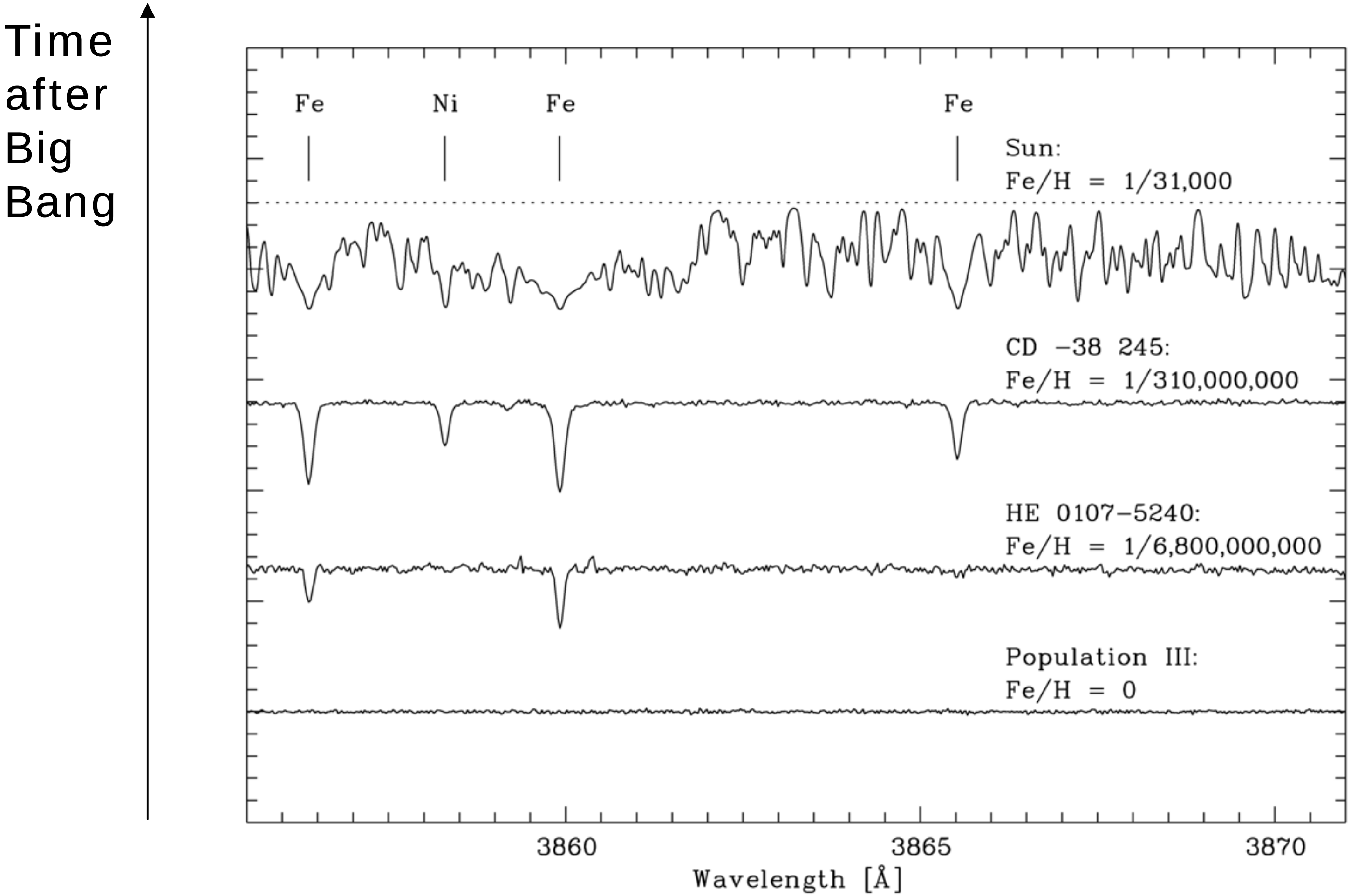
I. Introduction:
Why are we interested in the most metal-poor stars?

II. Selected recent achievements

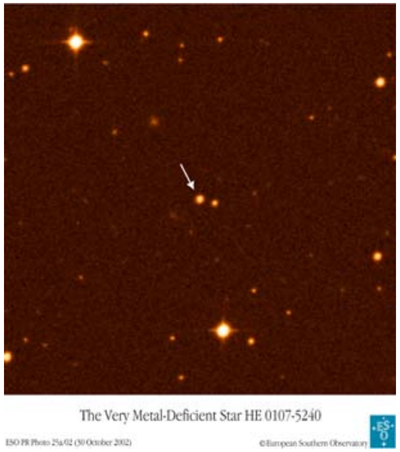
III. Opportunities for progress

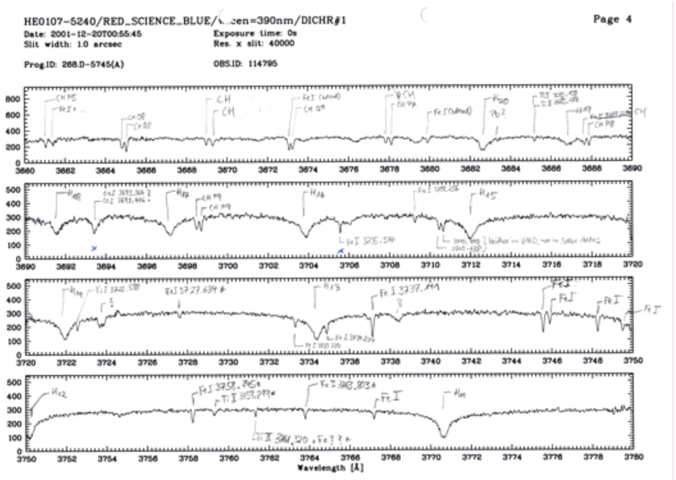
- **New surveys:** SEGUE, GAIA,...
- **Automated data analysis methods:**
  Stellar parameters, abundances,...
- **Larger telescopes:** CELT, OWL,...
- **More accurate abundances:** 3D models, non-LTE,...

# Metal-poor star look-back time



# Excavation of the oldest stars



# Metal-poor star topics

- What is the primordial Li abundance?
  => Test of BBN models, or determination of $\Omega_B$
- How old are the oldest stars?
  Age determination with nucleochronometry, e.g. Th/Eu; U/Th
- Star formation in low-metallicity environment
  Under which conditions can low-mass stars form?
- Initial Mass Function of the first generation of stars
  Top-heavy? Very Massive Stars?
- Constraining models of the first supernovae
  E.g., mixing, explosion energy, „mass cut“; via comparison of abundances of the most metal-poor stars with SN yields

# Metal-poor star topics (cont'd)

- Nucleosynthesis processes and their sites
  E.g., r-process, s-process; origin of carbon
- Galactic chemical evolution
  ISM mixing, star formation history, in- and outflow of gas, etc.
- Formation of the Galaxy
  E.g., correlations between abundances and kinematics, halo streams
- Evolution of zero and very-low metallicity stars
  Mixing, dredge-up, blue loop, 2nd RGB,...

End of Part I.

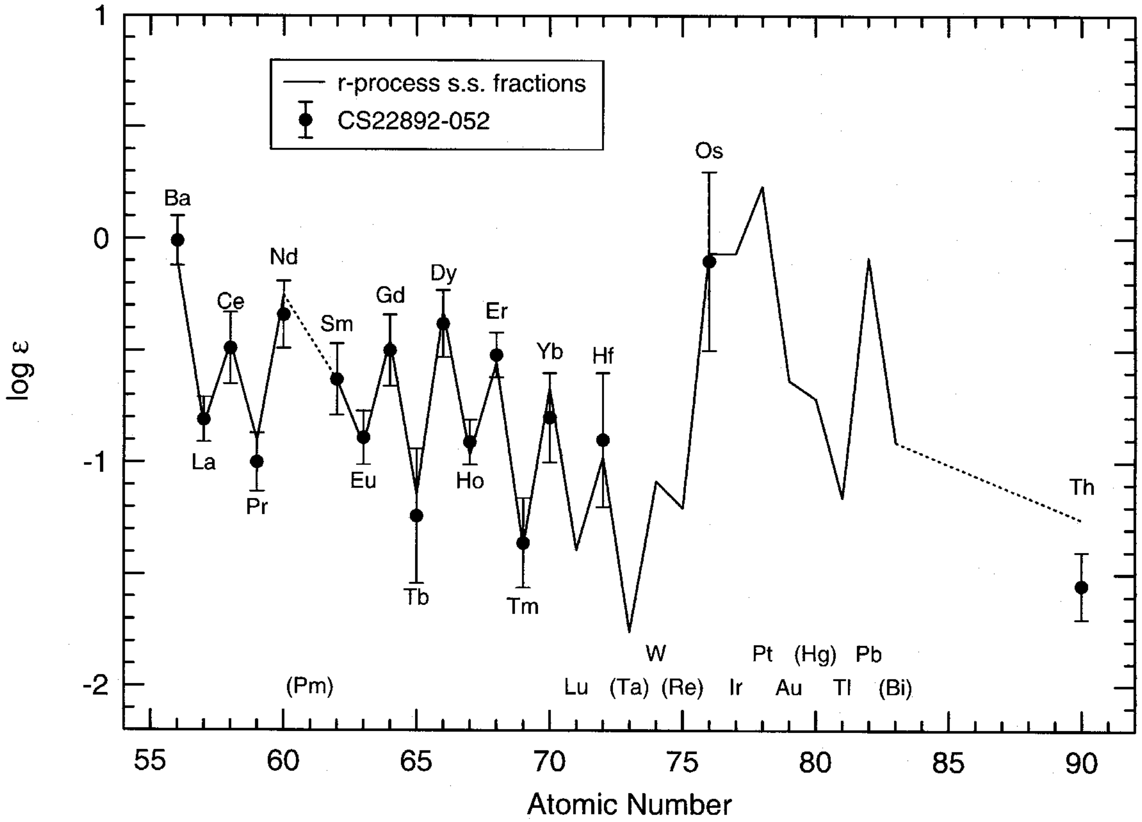
# Selected recent achievements

- Is the r-process universal?
- Age determination with uranium
- Scatter of abundance ratios
- Discovery of a star with [Fe/H] = –5.3

(For more complete review, see Beers & Christlieb 2004, ARAA, in preparation)

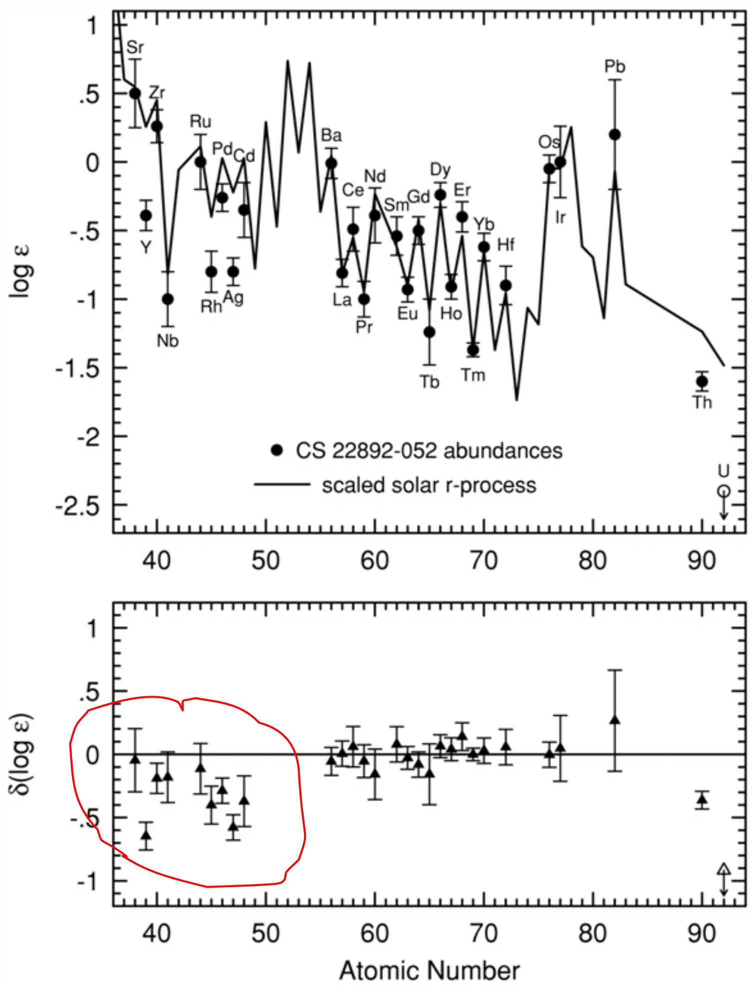
# CS22892–052

Also known as ***C**hris **S**neden's star* ;-)




Sneden et al. (1996)

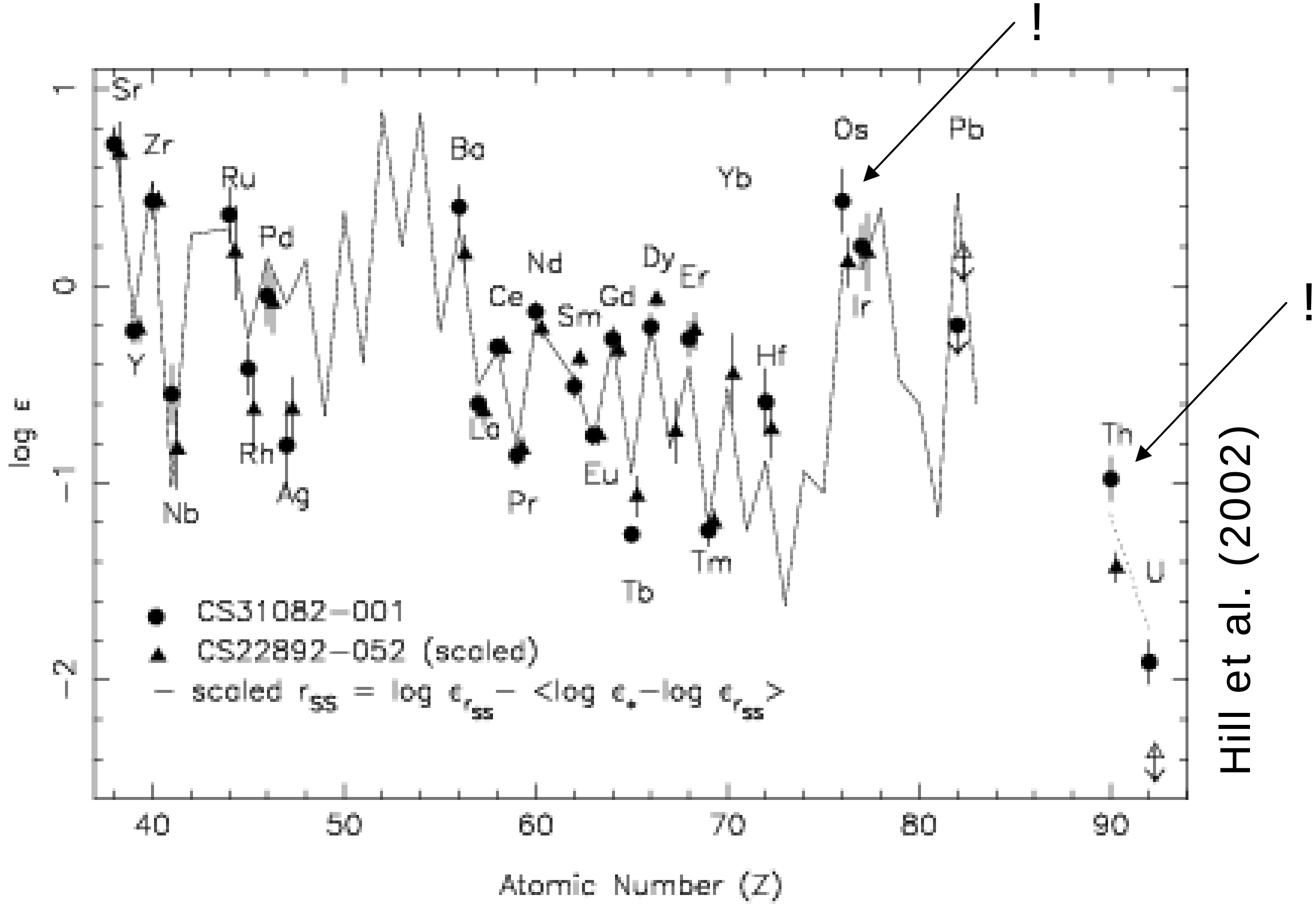
# CS22892–052




Sneden et al. (1997)

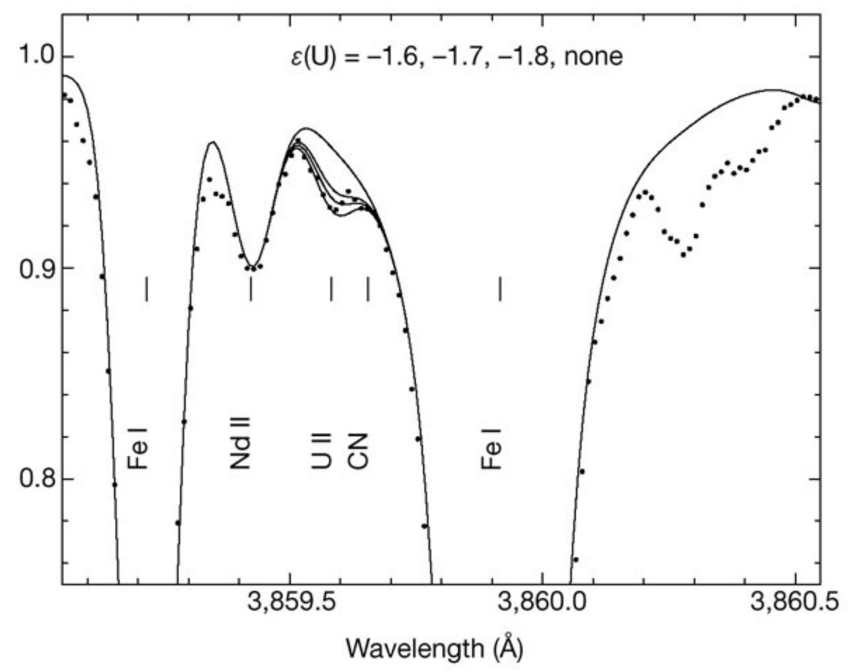
# CS31082–001

Also known as the *uranium star*

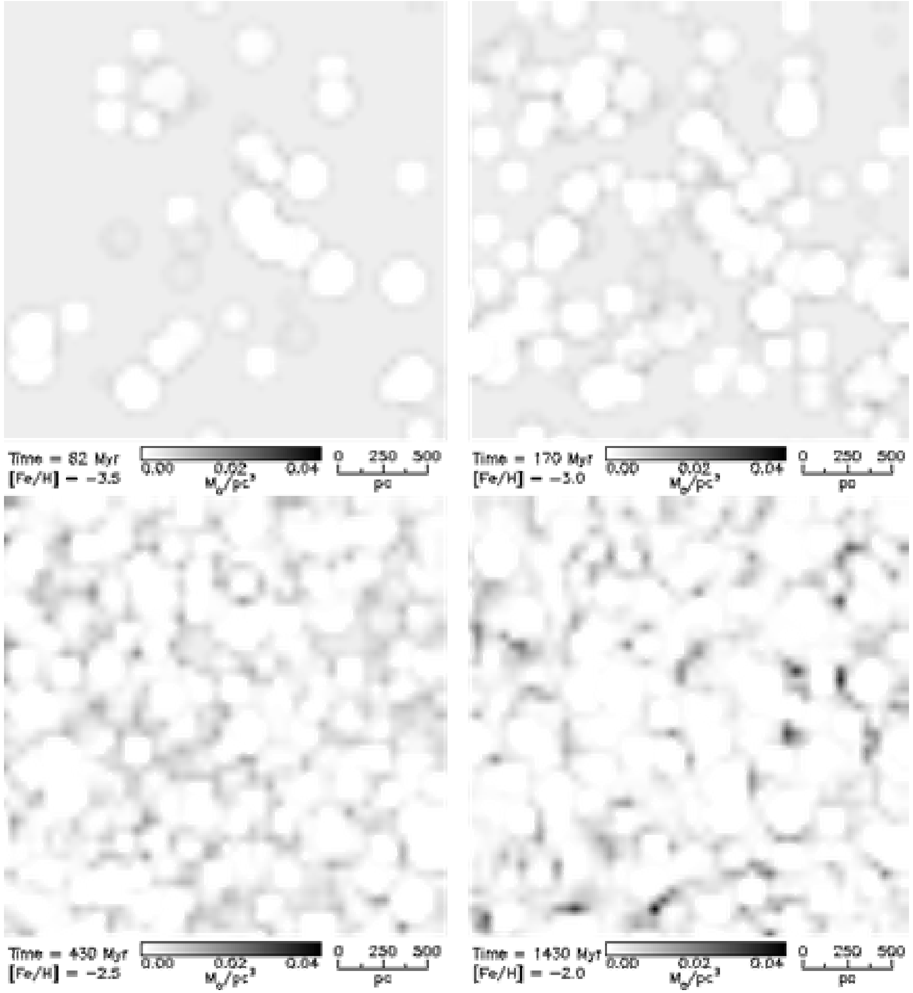


# CS31082–001

- Th: half-life 14 Gyr; U: 4.5 Gyr, therefore more precise age determinations possible with Th/U as compared to, e.g., Th/Eu
- Result for CS31082–001: 12.5±3 Gyr
- WMAP: Age of Universe is 13.7±0.2 Gyr



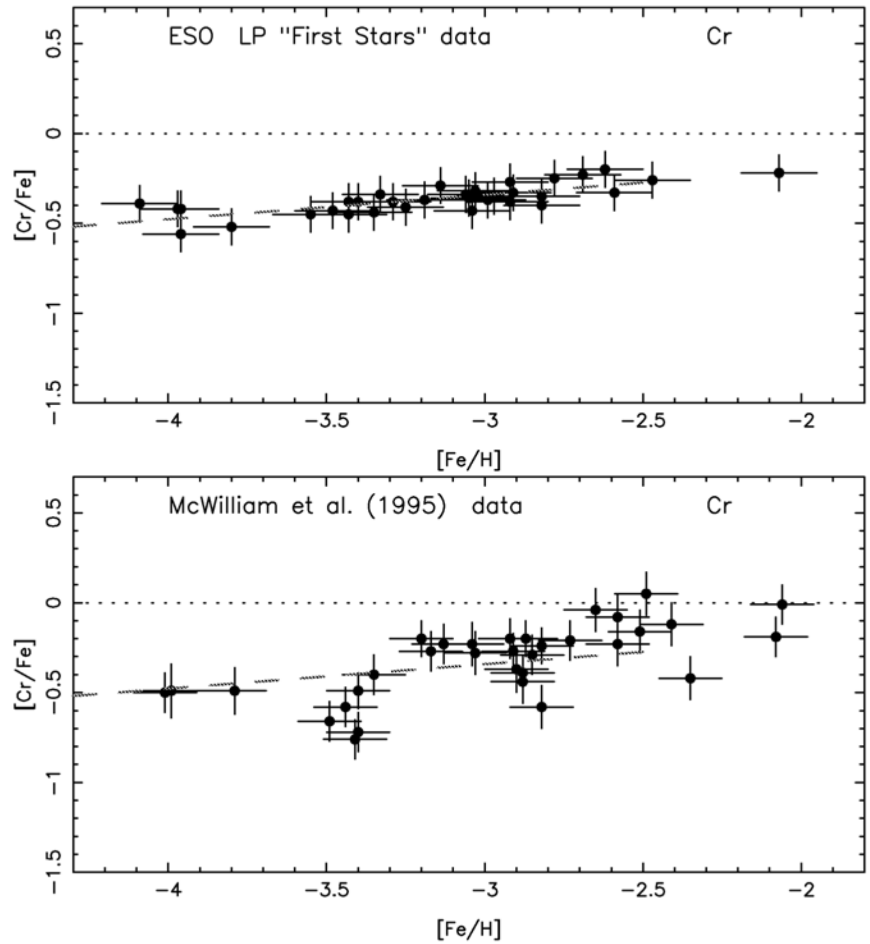
# Mixing of ISM




Argast et al. (2000), A&A 356, 873

# Observed scatter of abundances

- Previously observed abundance scatter appears to be mostly due to observational errors!
- Therefore, ISM might have been quite well-mixed already at low metallicities




Spite et al. (2003)

# HE 0107–5240: A giant with [Fe/H] = –5.3

| Parameter | Value | $\sigma$ |
|---|---|---|
| $T_{\rm eff}$ | 5100 K | 150 K |
| $\log g$ | 2.2 dex | 0.3 dex |
| [Fe/H] | −5.3 dex | 0.2 dex |
| $v_{\rm micr}$ | 2.2 km s$^{-1}$ | 0.5 km s$^{-1}$ |

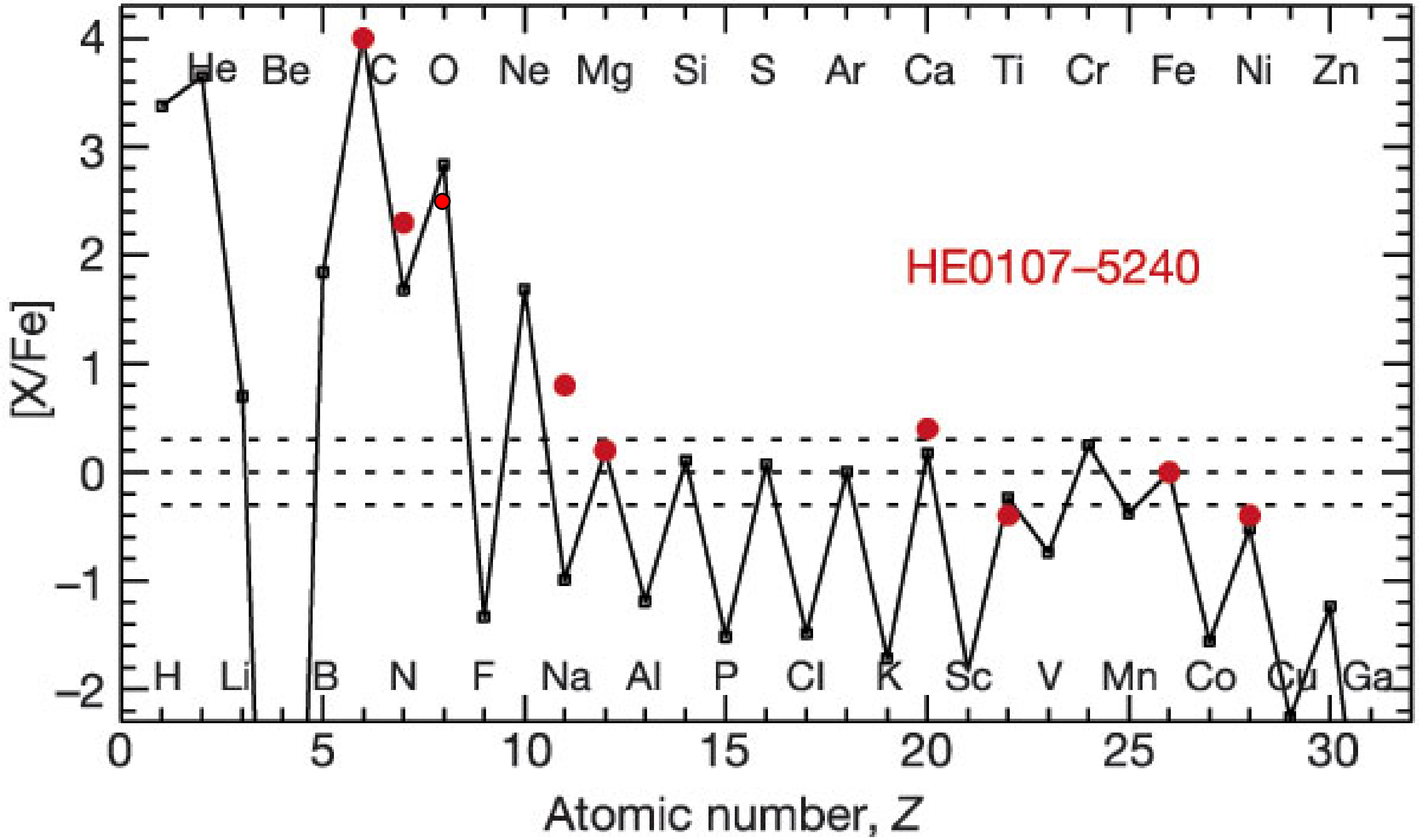
- Teff derived from Balmer line profile fits and photometry
- log g follows from 12 Gyr metal-poor star isochrone, and is constrained from absence of Fe II lines and relative strength of Balmer lines
- [Fe/H] derived from Fe I lines; takes into account NLTE correction of +0.11 dex

# Abundances of HE 0107–5240

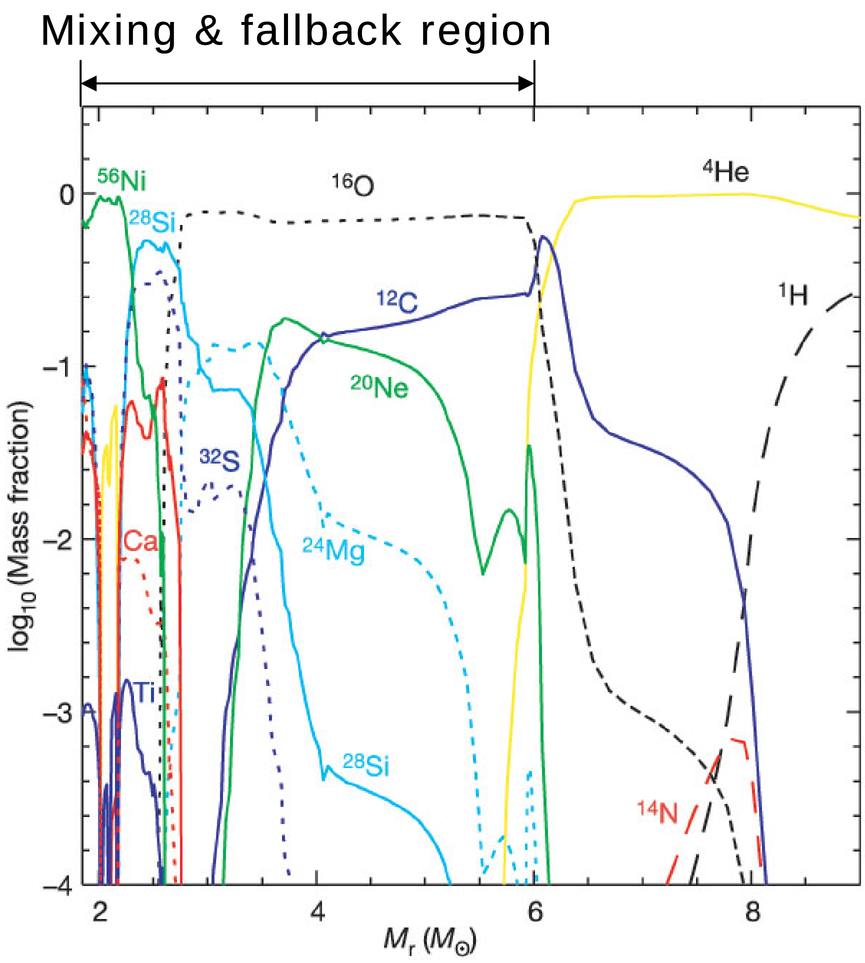
- Huge overabundances of C and N (+3.7–4.0 dex and +2.3–2.6 dex, respectively)
- $^{12}C/^{13}C > 40$
- [O/Fe] is about 2.4 dex (Bessell et al., in preparation)
- Na is enhanced by 0.8 dex
- $\alpha$-elements are up by the usual +0.4 dex
- Ti does not seem to follow $\alpha$-elements: down by –0.4 dex (NLTE not a problem since derived from Ti II lines)
- Ni seems to be flat: –0.4 dex measured from Ni I lines, but NLTE?
- *s*-process elements not strongly enhanced: Upper limit for [Ba/Fe] is +0.82; [Sr/Fe] < –0.5.

# Yields of Umeda & Nomoto (2003)

$25M_{Sun}$ Pop. III star exploding as SN with $E_{51}=0.3$; mixing & fallback



# Mixing & fallback

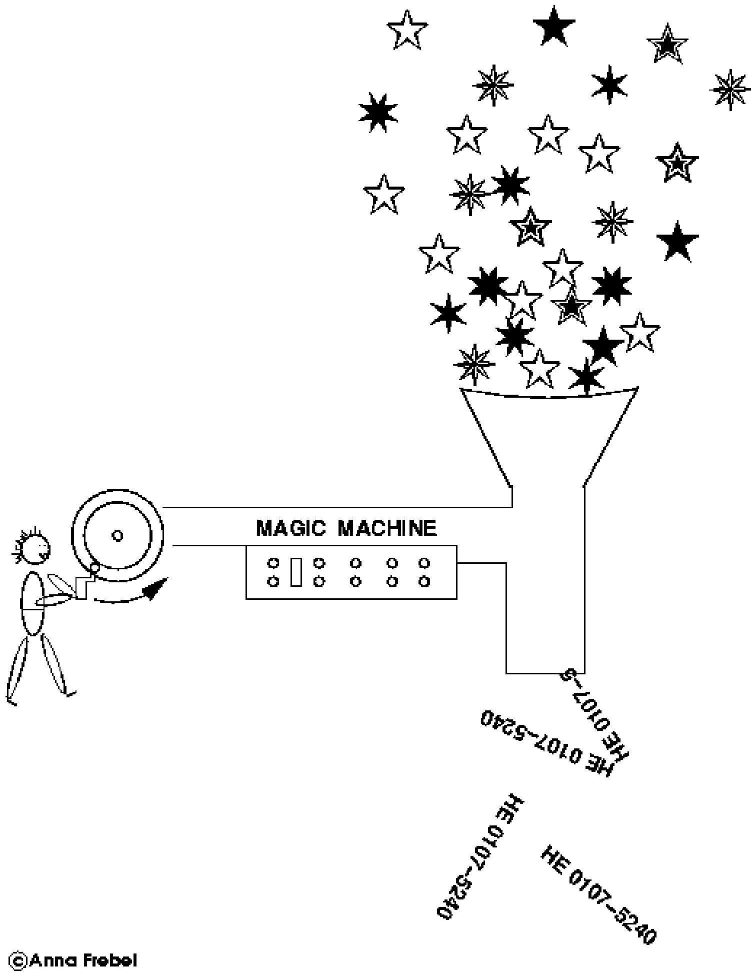


# What we can learn from HE 0107–5240

- Does the halo MDF *really* have a low-metallicity cutoff at [Fe/H] = –4.0?
- Low-explosion energy SN II in mass range 20–130 $M_{Sun}$ with mixing and fallback *might* play a dominant role in early Universe.
  This would also explain why we see so many stars with strong enhancements of C among the most metal-poor stars, and why many of them are not binaries.
- If CNO in HE 0107–5240 due to pre-enrichment, no cooling problem, because $Z \sim 10^{-2} Z_{Sun} >> Z_{crit} \sim 10^{-4} Z_{Sun}$.
- If *not* due to pre-enrichment, current theories of star formation in low-metallicity environment are challenged.

End of Part II.

# How to find metal-poor stars

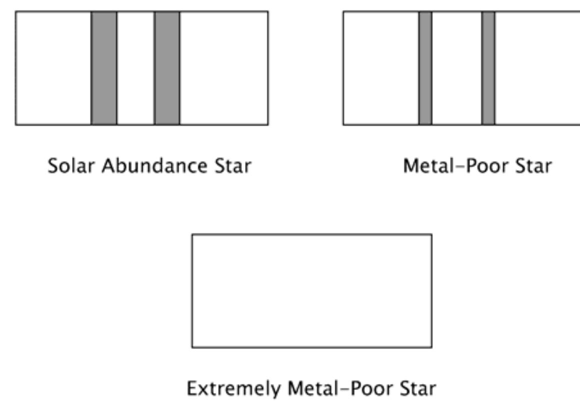


# The „classical“ approach

1. Wide-angle low-resolution spectroscopic survey
   i.e., objective-prism plates taken with Schmidt-telescope

2. Visual selection of metal-poor candidates

3. Moderate-resolution (~2Å) follow-up spectroscopy; determination of stellar parameters and [Fe/H], [C/Fe]

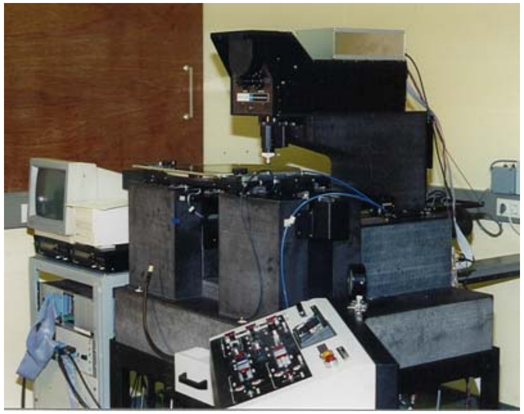


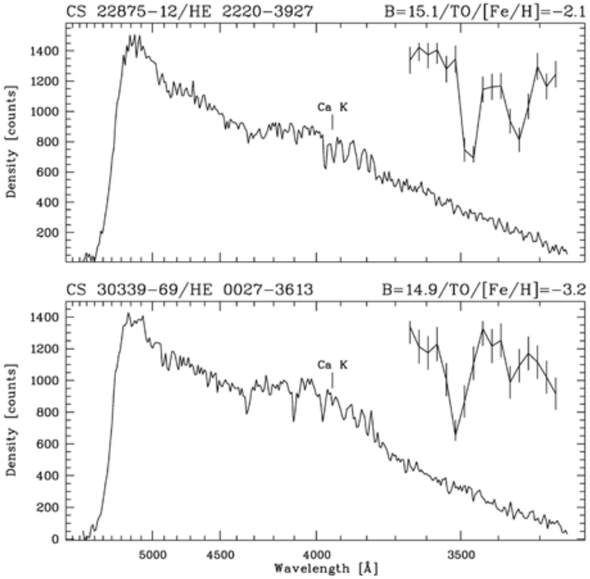
# A slightly more modern approach

1. Wide-angle low-resolution spectroscopic survey
   i.e., objective-prism plates taken with Schmidt-telescope; digitization with plate scanner

2. Automated selection of metal-poor candidates by applying quantitative criteria to digital spectra

3. Moderate-resolution (~2Å) follow-up spectroscopy; determination of stellar parameters, and [Fe/H], [C/Fe]





# Next generation metal-poor star surveys: What are the demands?

- Must be considerably deeper to increase survey volume
- Therefore, more efficient candidate selection needed, and/or increase of follow-up multiplexity
- Also, better defined samples needed to treat specific problems, e.g., study of r- and s-process, C-enhanced stars, etc.
  => „Snapshot spectroscopy“: R = 20,000; S/N = 30

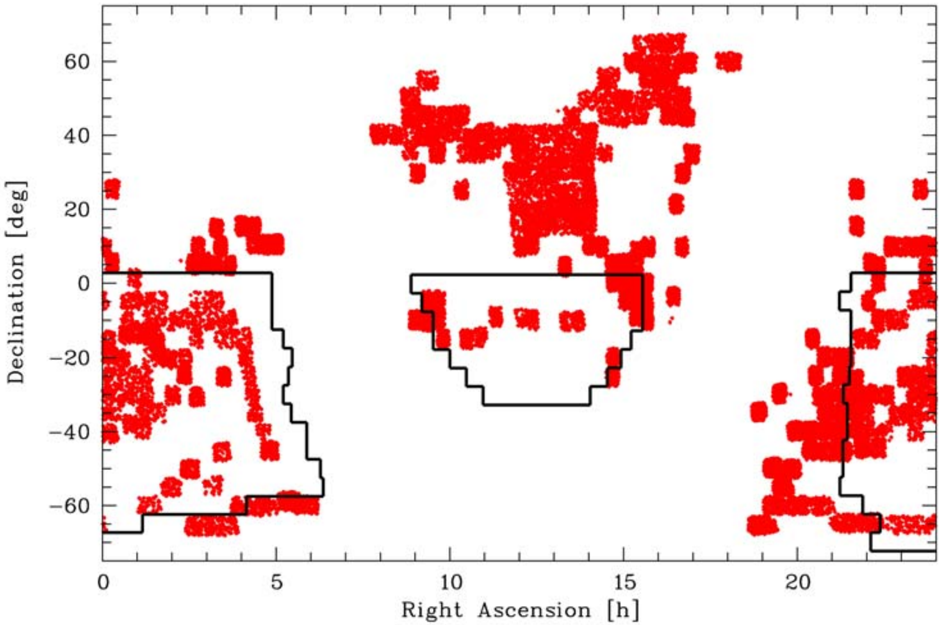
# Why survey volume is crucial

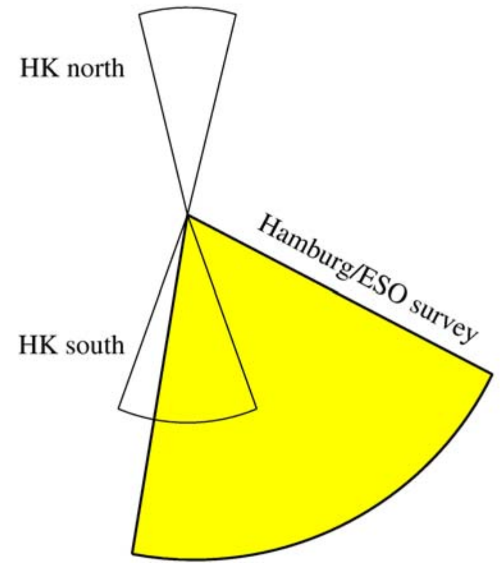
- HK survey:
  0 stars with [Fe/H]<–4.0
  among ~100 stars with [Fe/H]<–3.0

- HES (so far):
  1 star with [Fe/H]<–4.0
  among ~200 stars with [Fe/H]<–3.0

=> It‘s just a numbers game!

# Comparison of survey volumes




HES covers areas on the sky not covered by HK survey

HES is ~2 mag deeper than HK survey

Taking into account overlap in survey areas, the HES can increase total survey volume for metal-poor stars by a factor of ~8!

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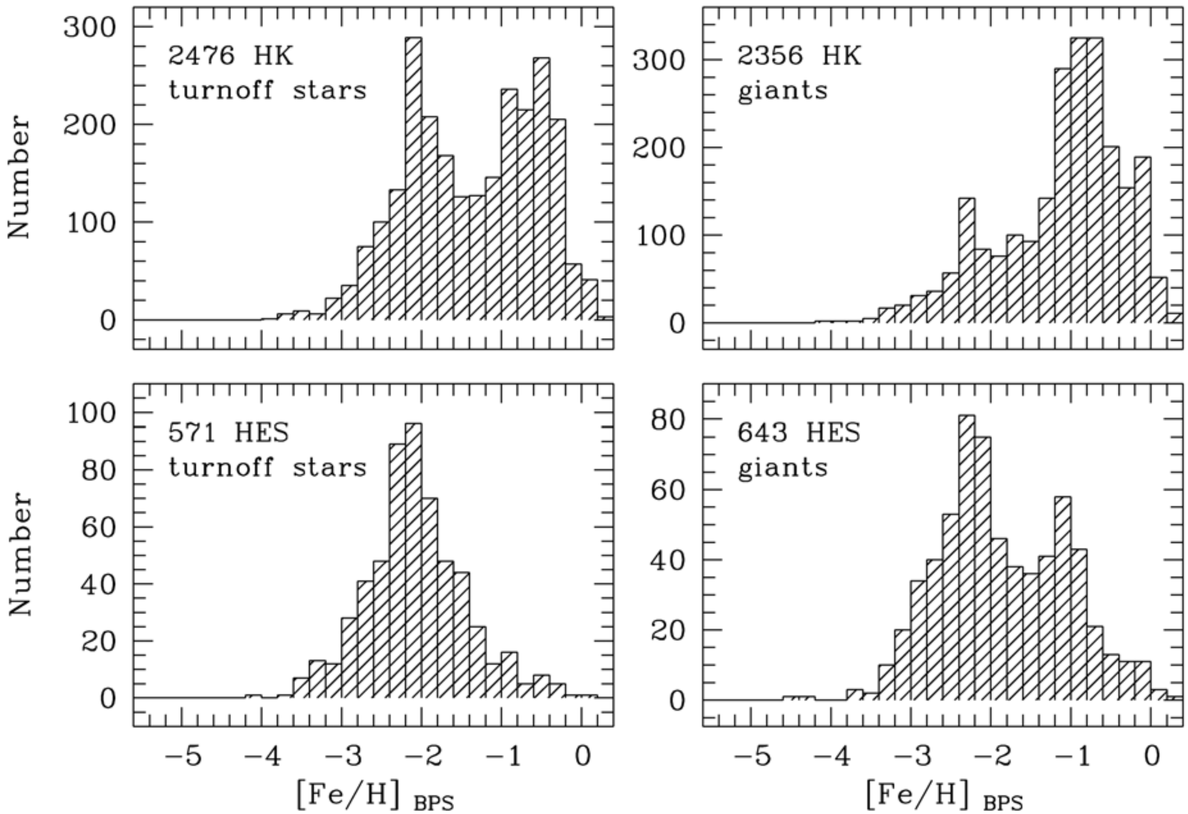
# Efficiency in finding metal-poor stars




Effective yields:
11% for [Fe/H] < –2
1% for [Fe/H] < –3

Effective yields:
55% for [Fe/H] < –2
6% for [Fe/H] < –3

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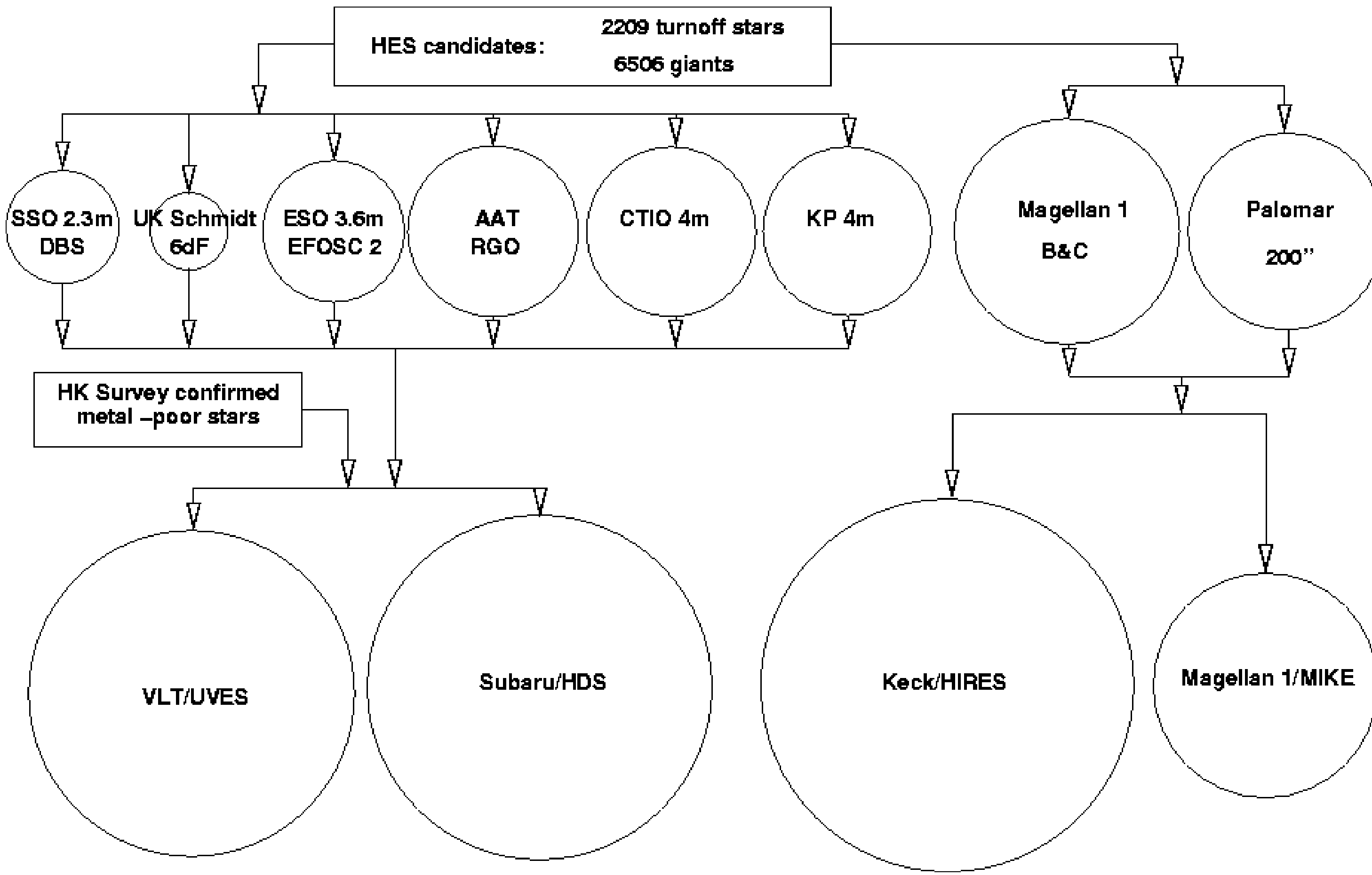
# The HES metal-poor star industry



# The HES metal-poor star industry

## Collaborators include:

Wako Aoki (NAOJ, Japan)
Martin Asplund (ANU, Australia)
Paul Barklem (Univ. Uppsala, Sweden)
Tim Beers (Michigan State Univ., USA)
Mike Bessell (ANU, Australia)
Judy Cohen (Caltech, USA)
Bengt Edvardsson (Univ. Uppsala, Sweden)
Anna Frebel (ANU, Australia)
Bengt Gustafsson (Univ. Uppsala, Sweden)
Vanessa Hill (Obs. de Paris, France)
Dionne James (AAO, Australia),
Torgny Karlsson (Univ. Uppsala, Sweden)

Andreas Korn (Univ. Uppsala, Sweden)
Andy McWilliam (OCIW, USA)
Michelle Mizuno-Wiedner (Univ. Uppsala)
John Norris (ANU, Australia)
Bertrand Plez (Univ. Montpellier, France)
Francesca Primas (ESO, Germany)
Jaehyon Rhee (Univ. Virginia, USA)
Silvia Rossi (IAGUSP, Brazil)
Sean Ryan (Open Univ., UK)
Ian Thompson (OCIW, USA)
Franz-Josef Zickgraf (Hamburg, Germany)

# Increasing follow-up multiplexity

SDSS Twin Spectrographs:
- 640 fibers per 3° field of view
- 3900–9100 Å covered at R=2000
- 3'' fibers

UK Schmidt/6dF:
- 150 fibers per 6° FOV
- R up to ~3000; coverage 820Å

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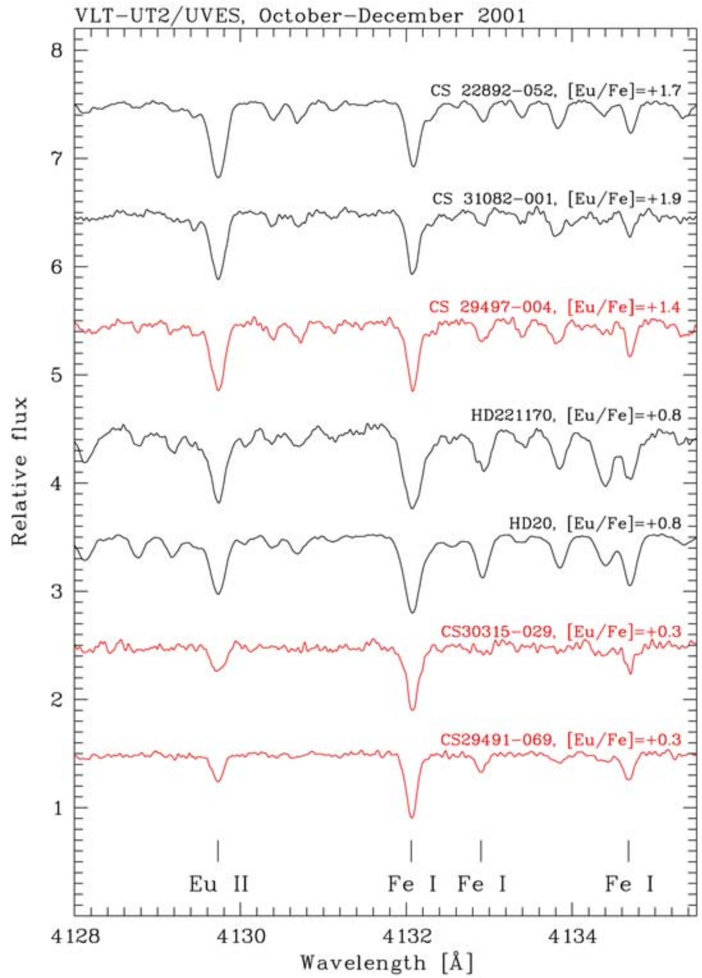
  => „Snapshot spectroscopy“: R = 20,000; S/N = 30

# Snapshot spectroscopy/VLT-UVES

- R = 20,000
- S/N = 30 per pixel at 4000Å
- Exposure times at VLT/UT2:
  *t* = 20 min for B = 16 mag star
- Aim: Observations of 500 metal-poor stars (~350 already done)

These spectra allow us to
- identify stars with strong enhancements of neutron-capture elements, and other interesting stars
- determine (rough) abundances for some 20 elements.



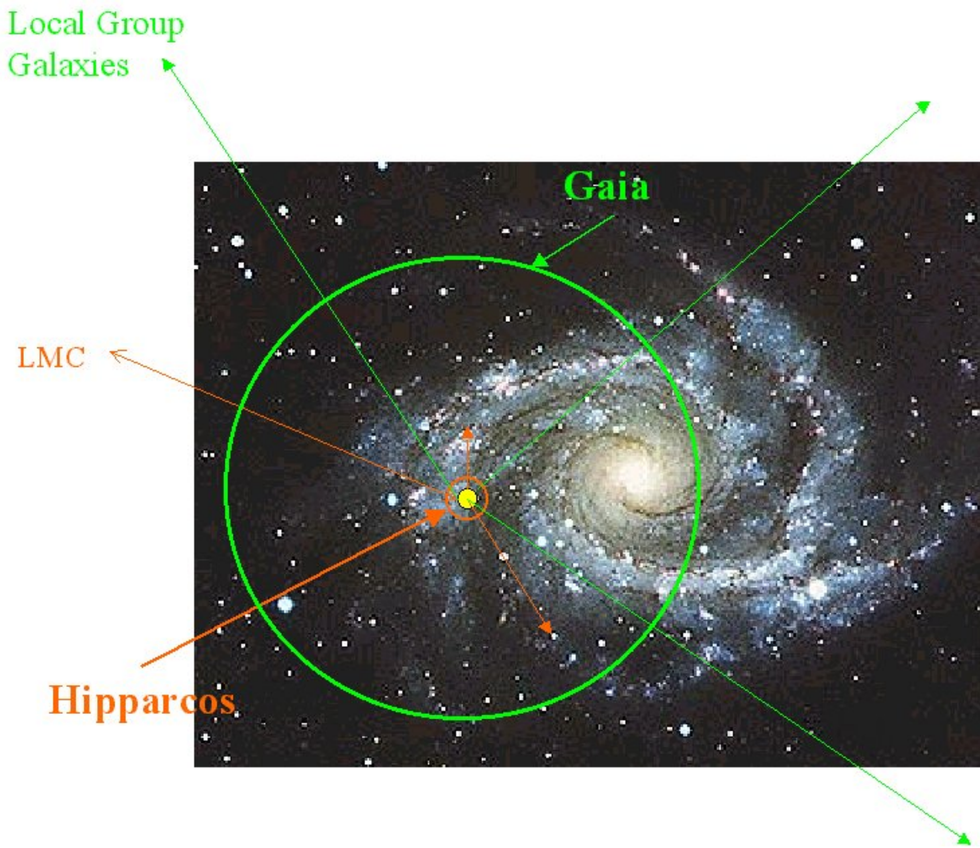
# Other possibilities for obtaining snapshot spectroscopy (?)

# Opportunities for new surveys

Examples:

- „Stellar extension“ of the Sloan Digital Sky Survey: SEGUE
  - Imaging: SDSS + 3000 $deg^2$ at low |b| and other directions
  - Spectroscopy: 250,000 stars; 14 mag < g < 20.3 mag
- GAIA
  - 1 billion stars down to V = 20 mag
  - Astrometry, radial velocities, intermediate-band photometry
  - Launch „not later than 2012“, but perhaps already 2009
  - For metal-poor stars, complementary observations from ground necessary

# GAIA



# Design Considerations

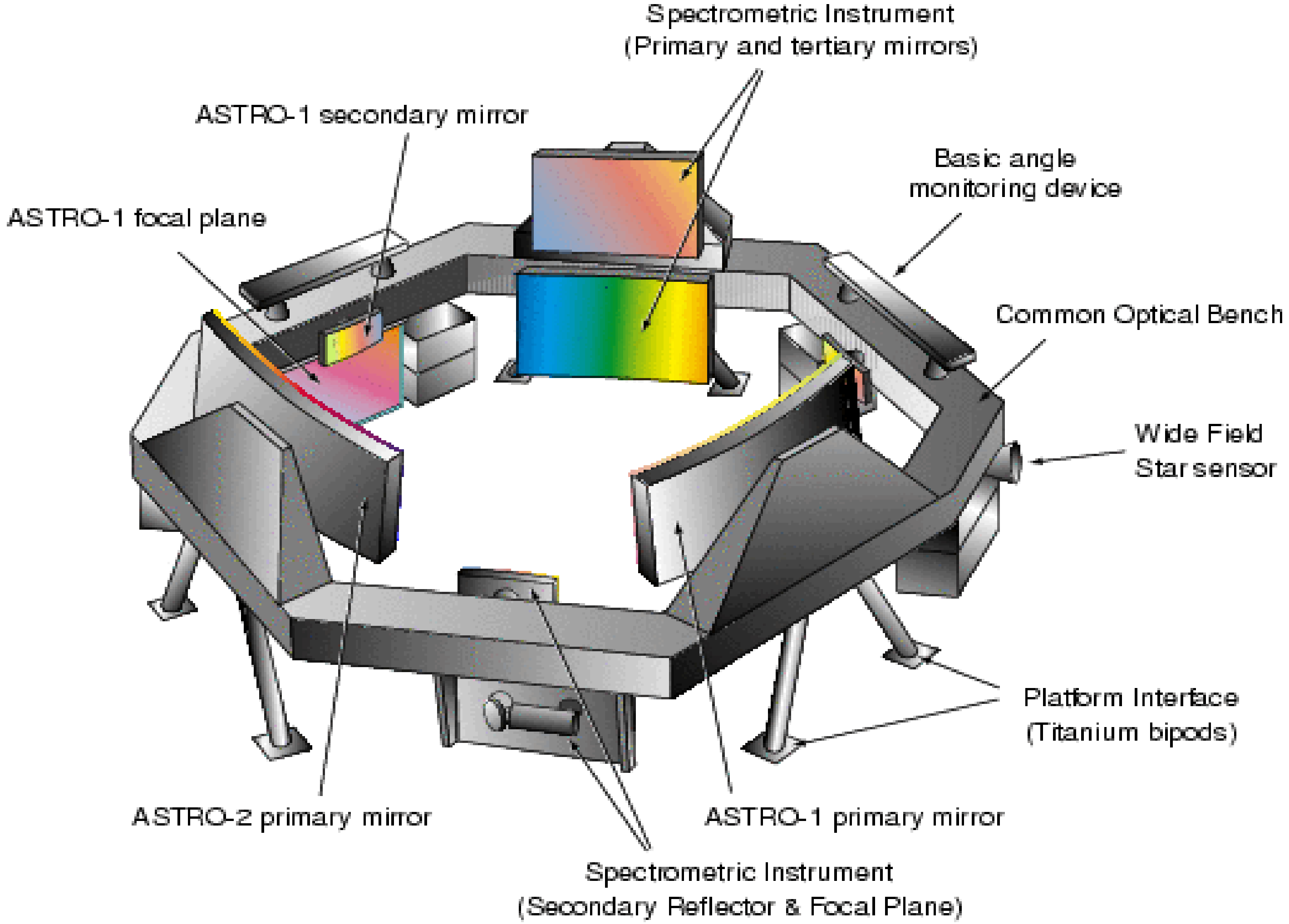
- Astrometry (V < 20 => $10^9$ stars!):
  - completeness ⇒ on-board detection
  - accuracies: 10 μas at 15 mag (Survey Committee + science)
  - scanning satellite, two viewing directions

    ⇒ global accuracy, optimal with respect to observing time
  - windowing reduces data rate from 1 Gbps to 1 Mbps
- Radial velocity (V < 17-18):
  - third component of space motion
  - measurement of perspective acceleration
  - astrophysical diagnostics, dynamics, population studies
- Photometry (V < 20):
  - astrophysical diagnostics (4-band + 11-band) + chromatic correction

    ⇒ extinction; $\Delta T_{eff}$ ~ 200 K, [Fe/H] to 0.2 dex

# Payload Configuration

–



# Automated data analysis

New, larger surveys require automated analysis of

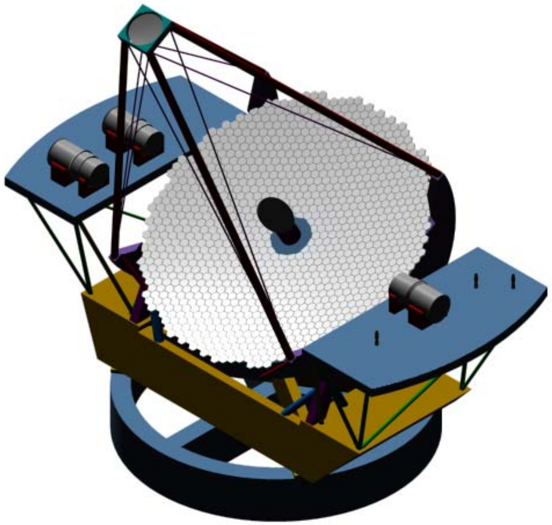
- survey data, i.e., quantative selection algorithms like automatic classification
  see e.g. Bailer-Jones et al./GAIA

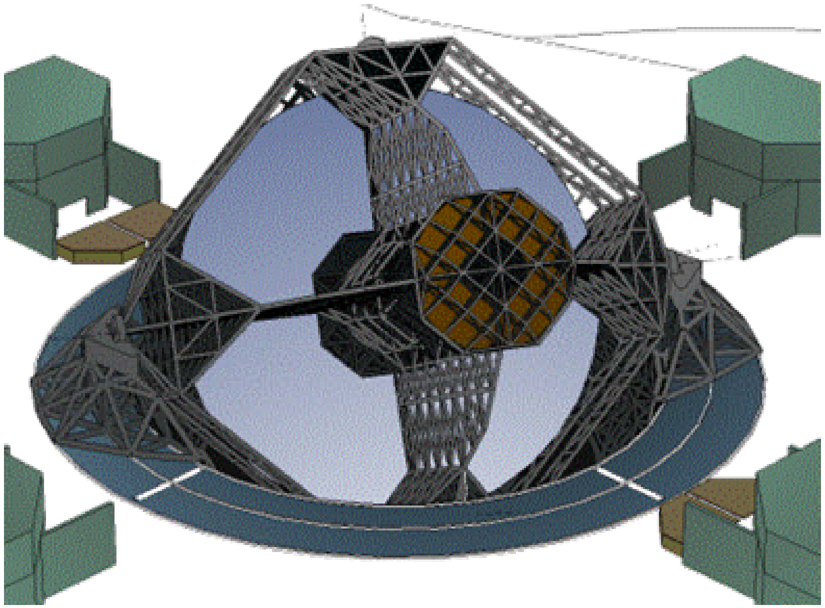
- moderate-resolution follow-up spectra/determination of stellar parameters, including [Fe/H]
  see e.g. Allende-Prieto et al./SDSS

- high-resolution spectra/abundance analysis
  see e.g. Barklem et al./VLT snapshot survey

# Why *we* want larger telescopes

The most interesting stars are very rare => larger survey volumes => fainter stars => less photons, and also, more photons required because lines in lowest metallicity stars very weak! => CELT, OWL, ...(any others?)

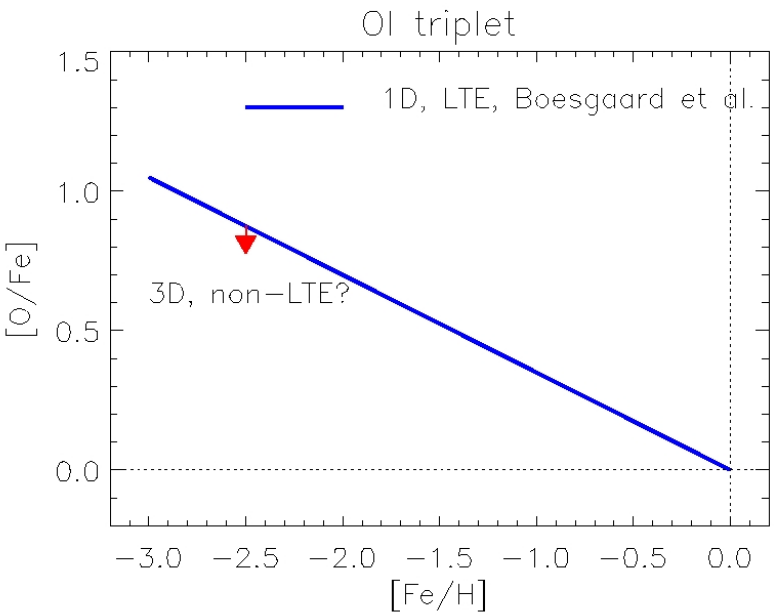


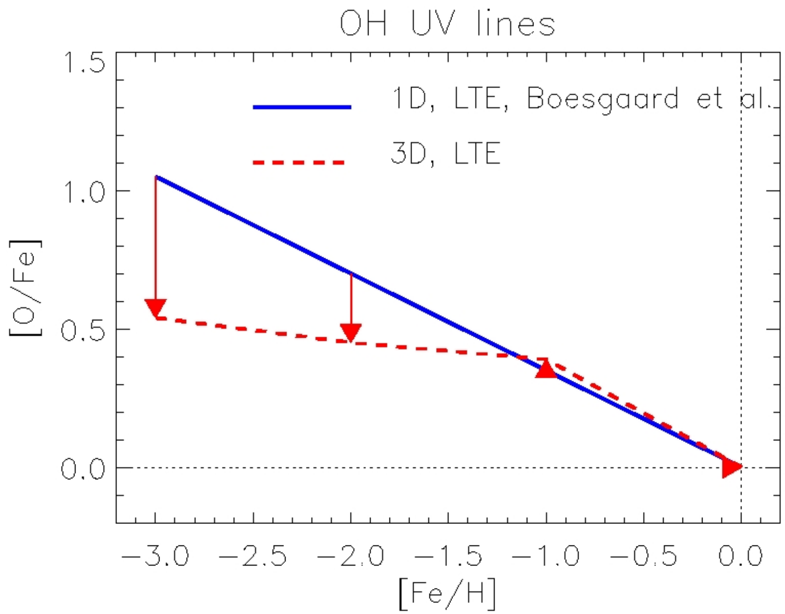


# Improvements of abundance analysis

Most important issues:

- 3D hydrodynamical models for cool stars
- NLTE line-formation




Asplund (2002)

# Revision of solar (!) abundances

| Element | Old (GS98) | New | Reference |
|---|---|---|---|
| C | 8.52 | 8.39 | Allende-Prieto et al. (2002) |
| N | 7.92 | 7.80 | Asplund (2003, priv. comm.) |
| O | 8.83 | 8.69 | Allende-Prieto et al. (2001) |
| Fe | 7.50 | 7.44 | Asplund et al. (2000) |
| Si | 7.55 | 7.51 | Asplund (2000) |

# Conclusion

In the next decade or so,

- we will have the opportunity to conduct new surveys with better survey techniques
- 30m+ telescopes have first light (hopefully...)
- we will be able to determine abundances of stars much more accurate.

Therefore, it will (continue to) be very exciting to work on metal-poor stars!

Astronomer by candlelight (Gerrit Dou, 1613-1675)

# THE END

Thank you for inviting me!