# Origin of Carbon-Enhanced Metal-Poor (CEMP) Stars

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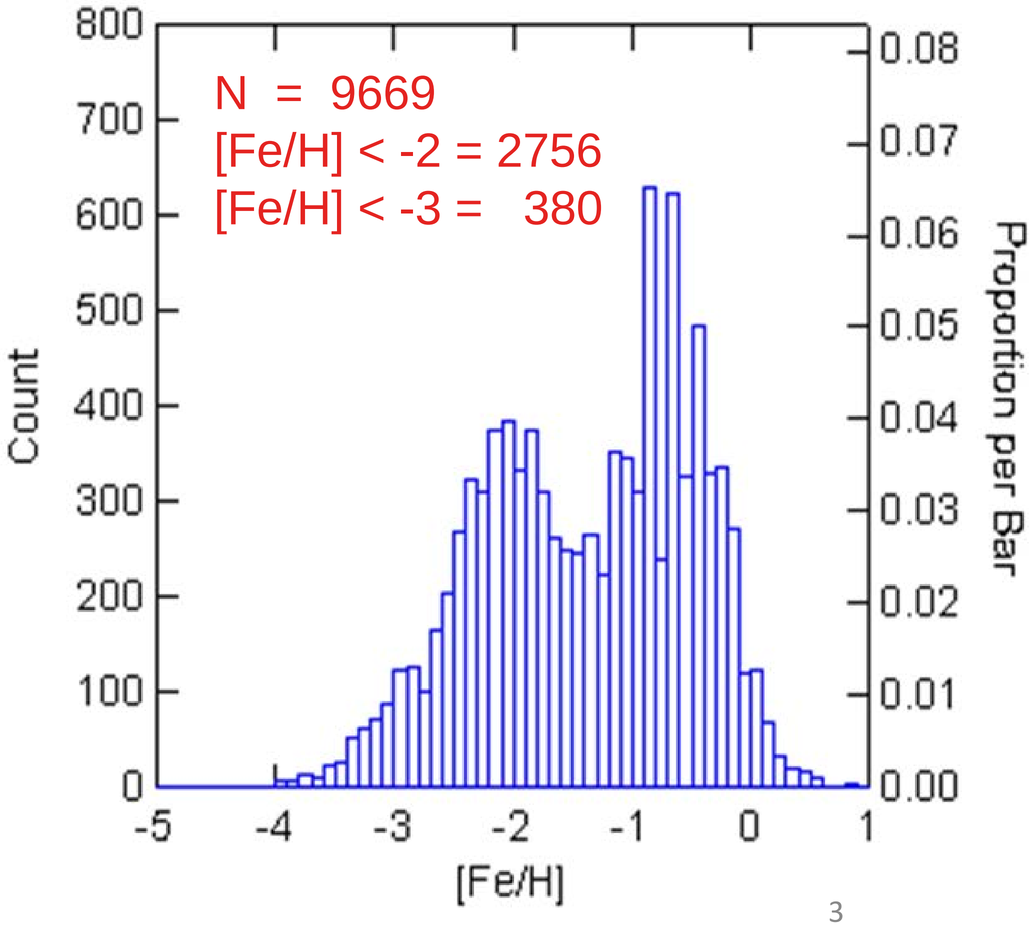
# Outline

- Metal-poor stars
- Discovery of carbon-enhanced metal-poor (CEMP) stars
- Properties and origin of CEMP stars
- High-resolution spectroscopy with Gemini/GRACES

# Metal-Poor (MP) Stars

- HK and HES(Hamburg ESO) surveys
  - ✓ Discovered several thousand very metal-poor (VMP; [Fe/H] < -2.0) stars
- Many tens of thousand VMP stars
  - ✓ SDSS (Sloan Digital Sky Survey)
  - ✓ SEGUE (Sloan Extension for Galactic Understanding and Exploration)
  - ✓ Ongoing SDSS IV (e.g., BOSS & eBOSS)
- Many more to come from LAMOST
  - ✓ LArges Multi-Object fiber Spectroscopic Telescope (LAMOST)
    - About 8 million stellar spectra will be obtained



# Known MP Stars – Pre and Post SDSS/SEGUE

- Nomenclature by Beers & Christlieb (2005)

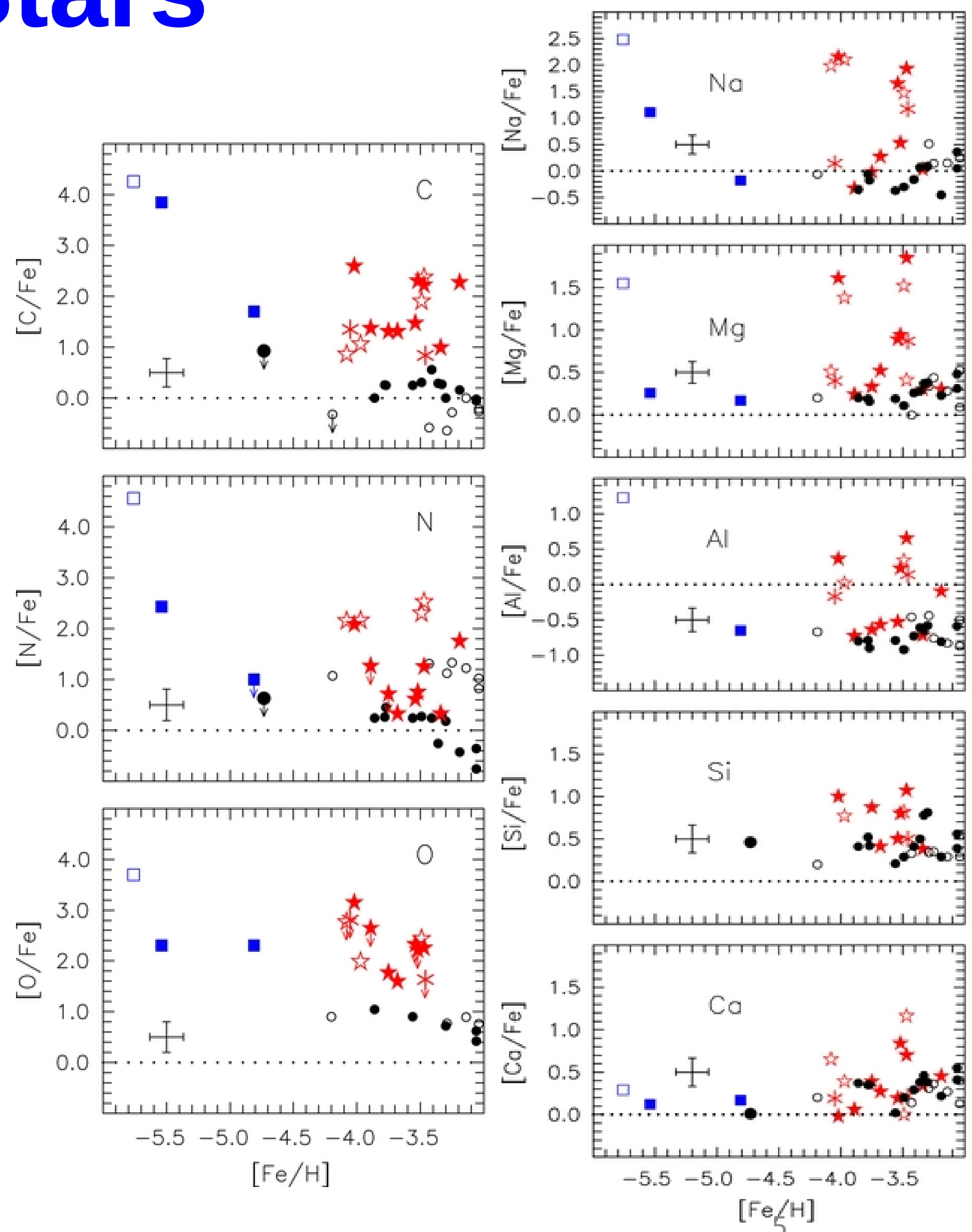
| Name | Metallicity | Pre | Post |
|---|---|---|---|
| Metal-Poor (MP) | [Fe/H] < -1.0 | 15,000 | 150,000+ |
| Very Metal-Poor (VMP) | [Fe/H] < -2.0 | 3,000 | 30,000+ |
| Extremely Metal-Poor (EMP) | [Fe/H] < -3.0 | 400 | 1000+ |
| Ultra Metal-Poor (UMP) | [Fe/H] < -4.0 | 6 | 21 |
| Hyper Metal-Poor (HMP) | [Fe/H] < -5.0 | 2 | 5 |
| Mega Metal-Poor (MMP) | [Fe/H] < -6.0 | 0 | 1 |
| Septa Metal-Poor (SMP) | [Fe/H] < -7.0 | 0 | 1 |
| Octa Metal-Poor (OMP) | [Fe/H] < -8.0 | 0 | 0 |
| Giga Metal-Poor (GMP) | [Fe/H] < -9.0 | 0 | 0 |

After 2014

Note that EMP stars potentially include additional UMP, HMP, MMP, SMP, OMP, or GMP stars

# Abundance Patterns of VMP Stars

- Detailed chemical-abundance analyses of VMP ([Fe/H] < -2.0) stars from the HK & HES surveys revealed:
  - ✓ Most VMP stars exhibit similar abundance pattern
  - ✓ But, there are peculiar objects with strong enrichments or deficiencies of light elements such as C, N, O, Na, Mg, Al, Si, Ca, etc.
  - ✓ Objects with ***carbon enhanced are the most common*** variety




Norris et al. (2013)

# Carbon-Enhanced Metal-Poor (CEMP) Stars

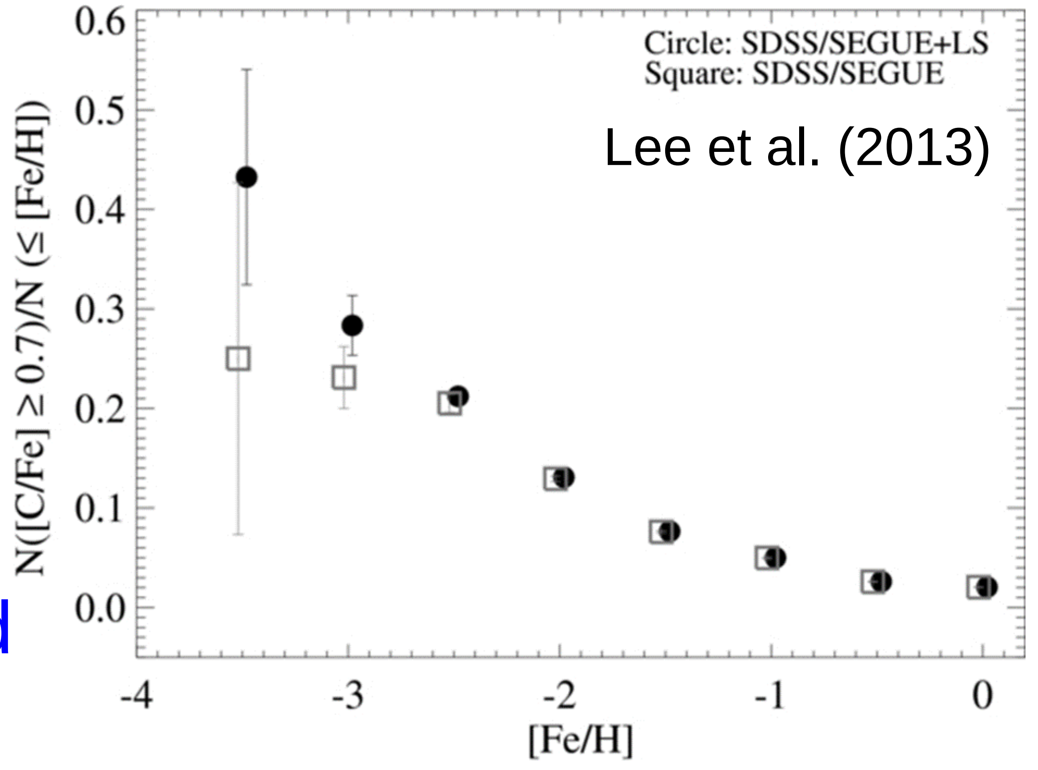
- CEMP
  - ✓ Carbon-Enhanced Metal-Poor (CEMP)
  - ✓ CEMP stars defined by [Fe/H] < -1.0 and [C/Fe] > +1.0 (or [C/Fe] > +0.7) (Beers & Christlieb 2005)
- [C/Fe]
  - ✓ Coin a term “Carbonicity” similar to Metallicity ([Fe/H]) (e.g., Carollo et al. 2012)

# Frequency of CEMP Stars

- ❑Largest list (~4800) of CEMP stars ever made from SDSS/SEGUE
- ❑Fraction of CEMP stars increases as the metallicity decreases
  - ✓Generally CEMP star frequencies are:
    - •20% for [Fe/H] < -2.5
    - •30% for [Fe/H] < -3.0 EMP
    - •40% for [Fe/H] < -3.5
    - •75% for [Fe/H] < -4.0 UMP
    - •100% for [Fe/H] < -5.0 HMP
- ❑What does this mean?

➔ A large amount of carbon was produced in the early history of the Milky Way

➔ Then, a question arises "**how?**"



# Subclasses of CEMP Stars

- Another interesting aspect of CEMP stars is that they have different enhancement of n-capture elements
- CEMP Stars are further divided into four groups depending on the enhancement of the s-process element (Ba) or r-process element (Eu)

| Carbon-enhanced metal-poor stars | |
|---|---|
| CEMP | [C/Fe] $> +1.0$ |
| CEMP-r | [C/Fe] $> +1.0$ and [Eu/Fe] $> +1.0$ |
| CEMP-s | [C/Fe] $> +1.0$, [Ba/Fe] $> +1.0$, and [Ba/Eu] $> +0.5$ |
| CEMP-r/s | [C/Fe] $> +1.0$ and $0.0 <$ [Ba/Eu] $< +0.5$ |
| CEMP-no | [C/Fe] $> +1.0$ and [Ba/Fe] $< 0$ |

Note that CEMP-s and CEMP-no stars account for over 95%

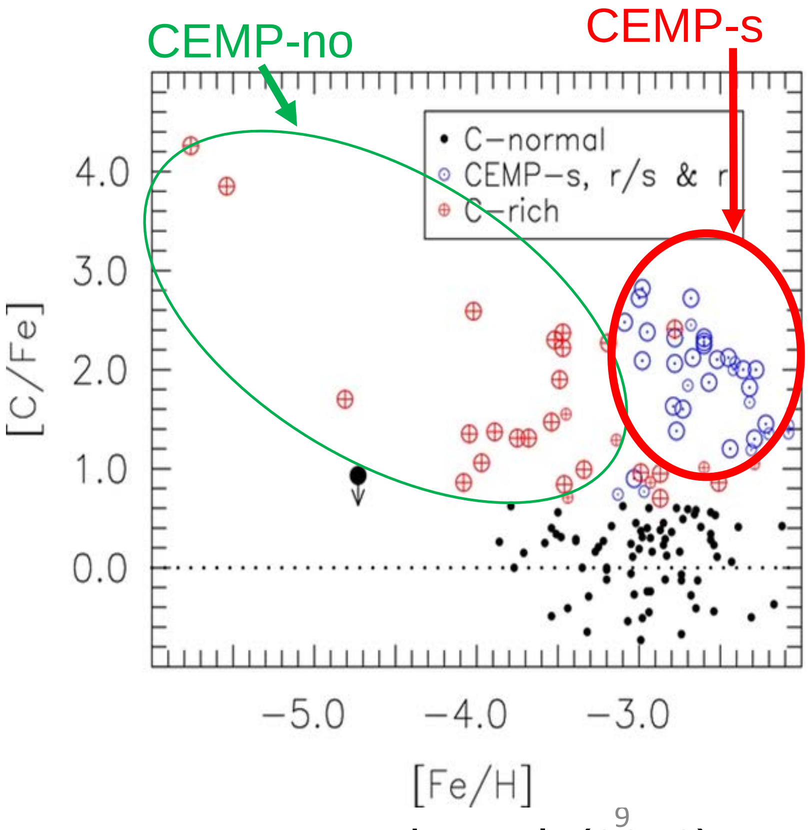
- What does this imply?

→ Indicative of different astrophysical sites to produce these objects at early times

# Properties and Origin of CEMP Subclasses

- Various subclasses of CEMP stars
  - ✓ CEMP stars in the Galaxy are likely produced by multiple mechanisms
  - ✓ Need to investigate properties of each subclass

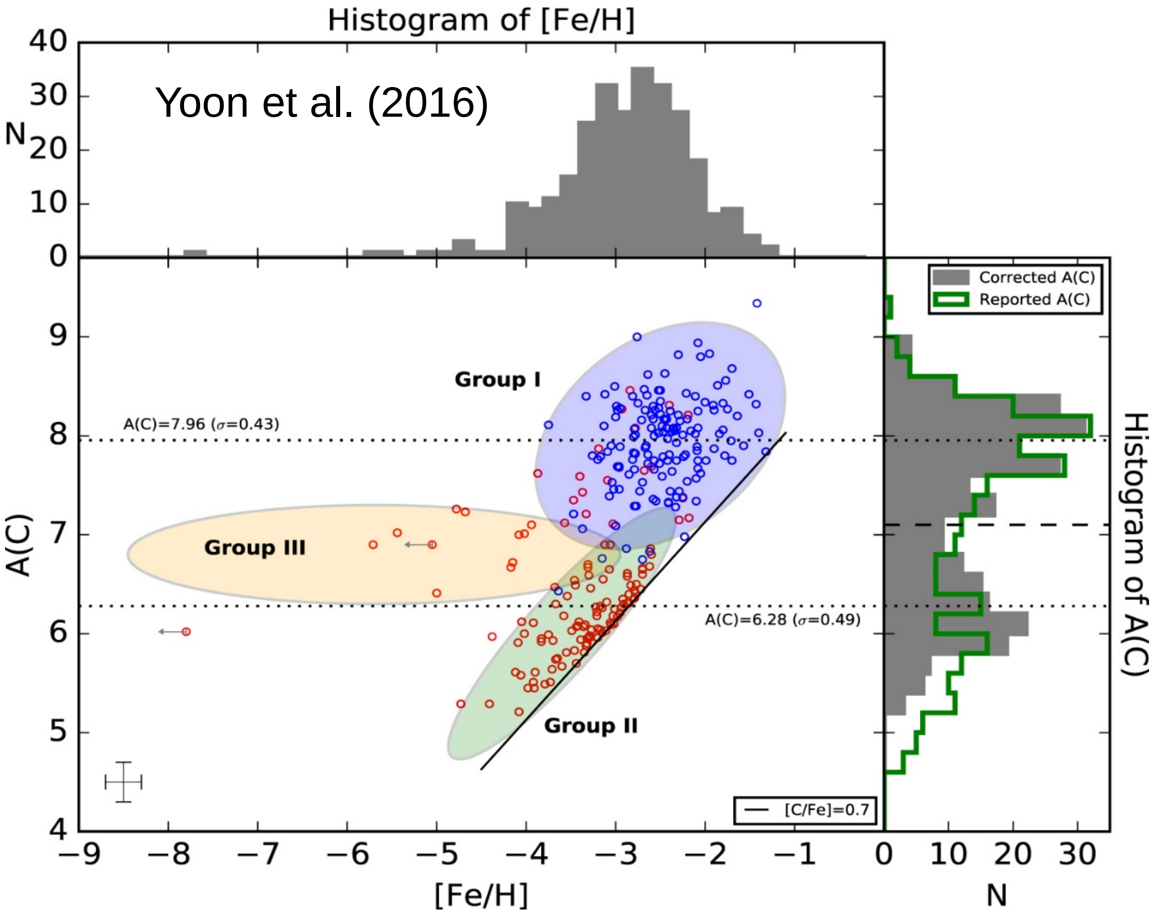
| | CEMP-s | CEMP-no | CEMP-r/s | CEMP-r |
|---|---|---|---|---|
| Fraction | > 80% | ~15% | < 2% | < 2% |
| Metallicity range | [Fe/H] > -3.0 | [Fe/H] < -3.0 | [Fe/H] > -3.0 | [Fe/H] > -3.0 |
| RV variation | Yes (> 80%) | No (> 83%) | Yes | No (?) |
| Possible progenitor | Low mass Pop II | High mass Pop III | Low mass Pop II | Intermediate mass Pop II (?) |
| Favored mechanism | AGB binary mass transfer | Spinstars Faint SNe | AGB binary mass transfer | SNe (?) |




Norris et al. (2013)

# Recent Development on CEMP-no Stars

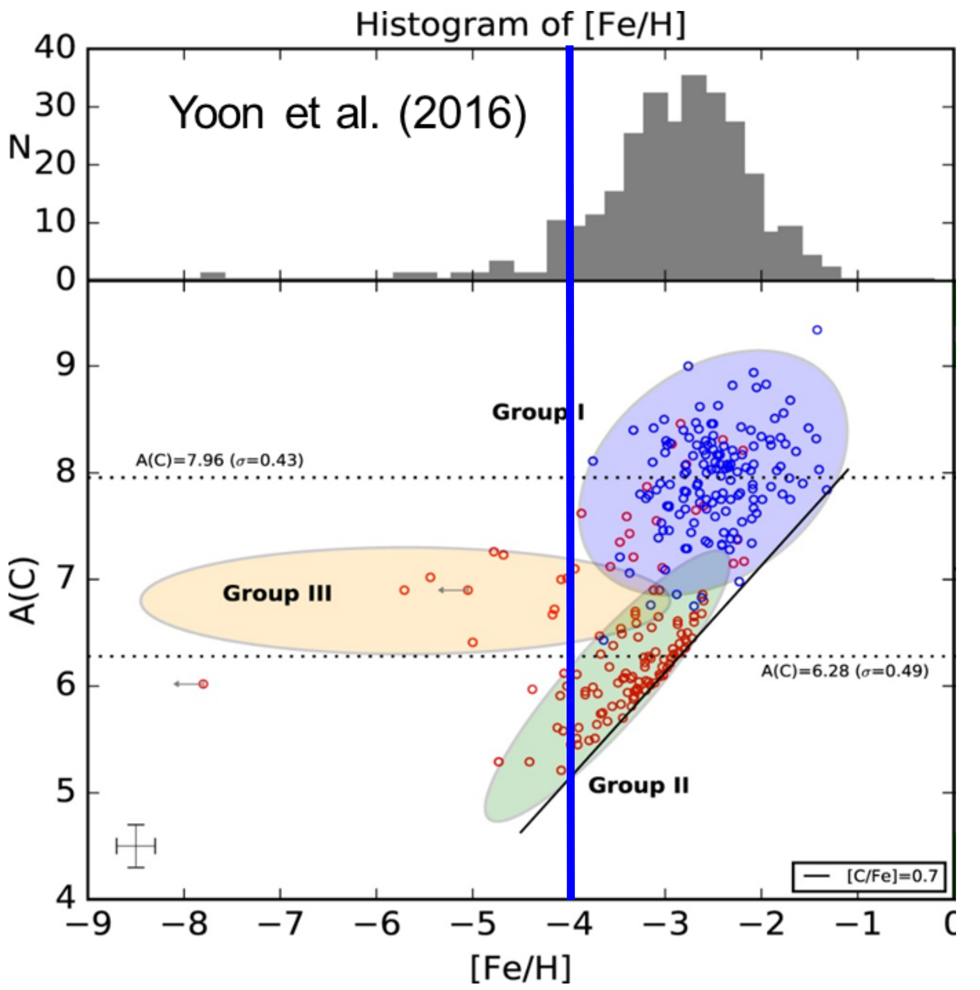
- ❑More separation on CEMP-no stars
- ❑Group I – CEMP-s, -r, -r/s
  - ✓Associated with Pop II AGB stars or SNe
- ❑Group II – CEMP-no
  - ✓Correlation of A(C) with [Fe/H]
  - ✓High mass Pop III faint SN progenitors?
- ❑Group III – CEMP-no
  - ✓No correlation of A(C) with [Fe/H]
  - ✓Smaller numbers relative to Group II
  - ✓High mass Pop III spinstar progenitors ?




➔ At least two possible progenitors exist for CEMP-no stars !

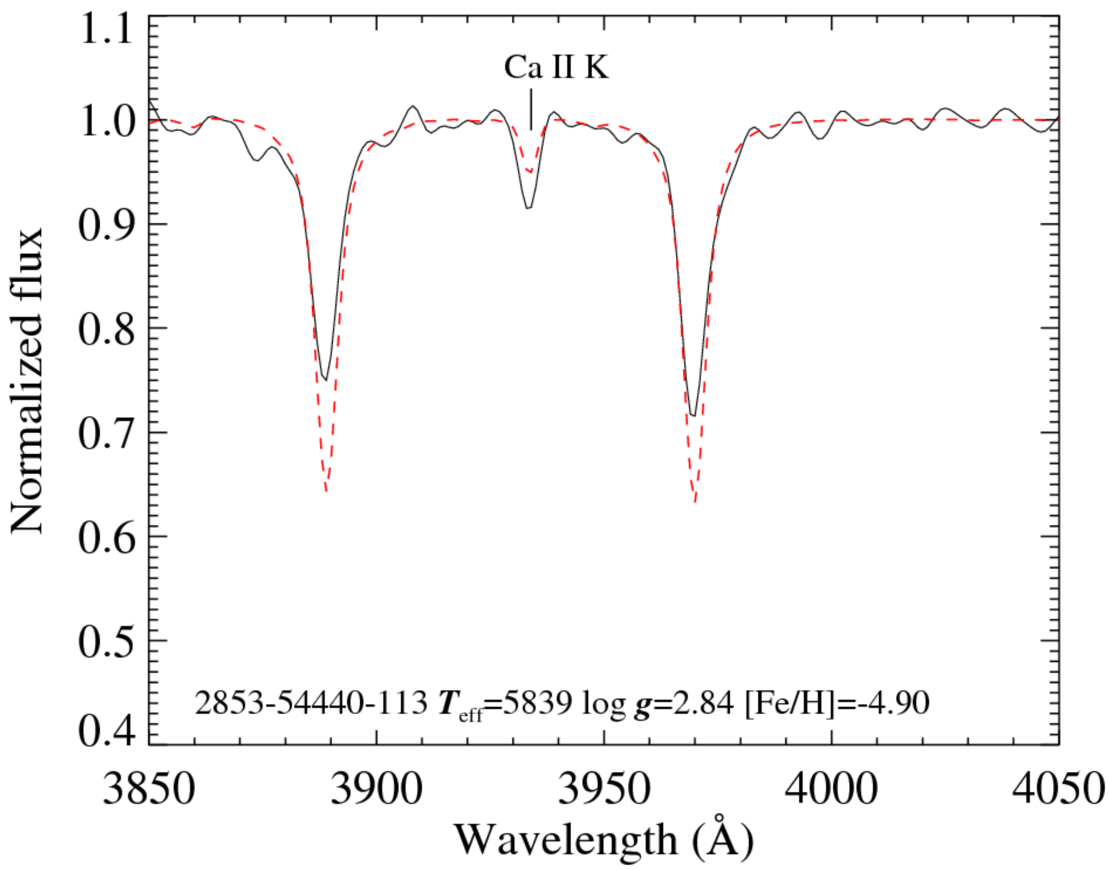
# Recent Development on CEMP-no Stars

- Characterization of progenitors for Group II and Group III
  - ✓ Need more detailed abundances for a larger number of UMP ([Fe/H] < -4.0) stars
  - → High-resolution spectroscopy with large telescopes comes into play
  - ✓ Require further elaborate theoretical models to explain abundance patterns



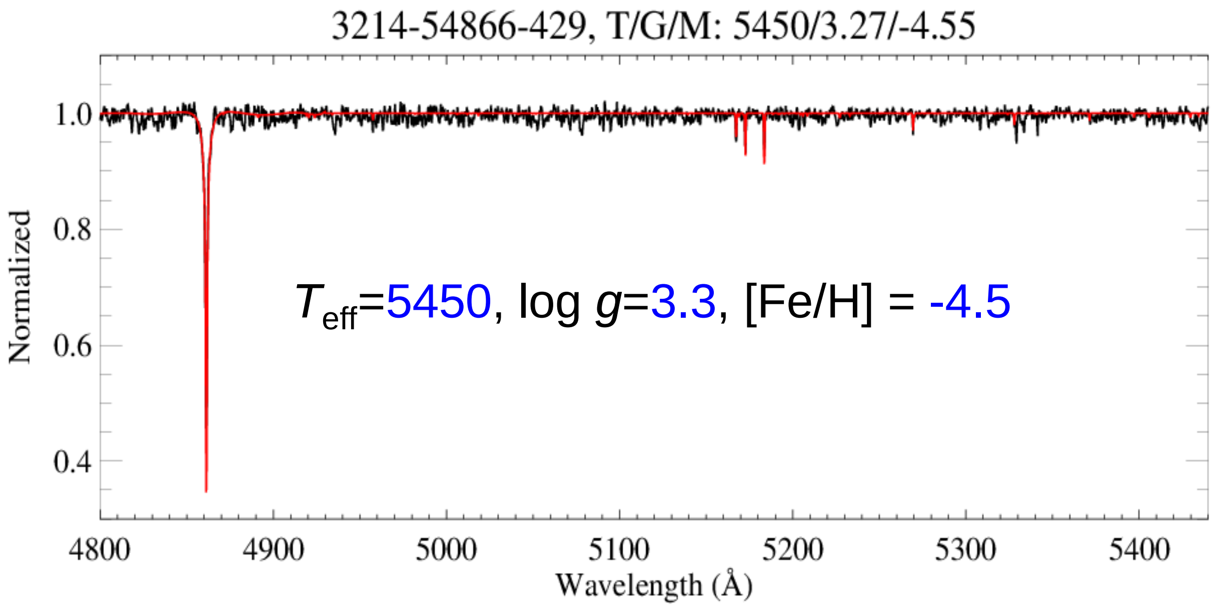
# Search for UMP Stars with Gemini/GRACES

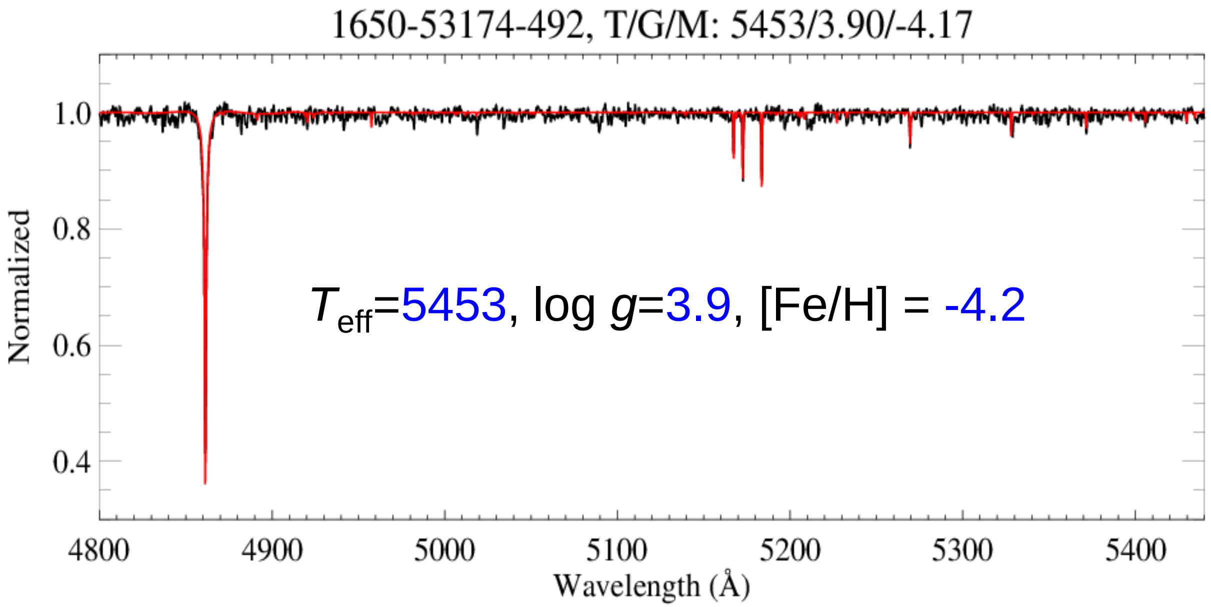
- Gemini/GRACES observation of candidates with [Fe/H] < -4.0
  - ✓ Targets were selected from the SDSS
  - ✓ Selection criteria
    - [Fe/H] < -3.5 measured from Ca II K line
    - 4500 < $T_{eff}$ < 6500 K
  - ✓ Six candidates and one reference star were observed
  - ✓ Two fiber mode
    - Resolving power of *R*~40,000
  - ✓ Data reduction & abundance analysis
    - Li, C, O, Na, Mg, Ti, Cr, Fe, Sr, Ba, Eu, etc.
    - Characterization of progenitors of these objects



# Search for UMP Stars with Gemini/GRACES

- Preliminary results from Gemini/GRACES spectra – stellar parameters
  - ✓ Reference star: 3214-54866-429
    - $T_{eff}$=5467, log $g$=3.2, [Fe/H] = -4.34 (Placco et al. 2015)




  - ✓ Identified five of six stars as UMP stars
  - ✓ Detailed chemical abundance analysis is underway

# Looking Forward for GMT

- Need to expand the number of UMP ([Fe/H] < -4.0) stars
- Lots of faint UMP candidates in SDSS/LAMOST
  - ✓ Mostly too faint (*g* > 17) for 8~10m class telescopes
  - ➔ Really good targets for GMT/G-CLEF
- Detailed abundance analysis from high-resolution follow-ups
  - ✓ Establish the accurate frequency of CEMP stars as a function of [Fe/H]
    - ➔ Possible to infer the initial mass function (IMF)
  - ✓ Provide more stringent constraints to the formation models of CEMP subclasses
  - ✓ Understand nucleosynthesis of heavy elements in the Pop III stars
- Gemini Korean time is a good opportunity for training young Korean astronomers with high-resolution stellar spectroscopy in this field ➔ preparation for the GMT