Non-Local Chemical Enrichment in the Early Galaxy

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Standard Chemical Evolution Models

Conventional model: Enrichment of ISM

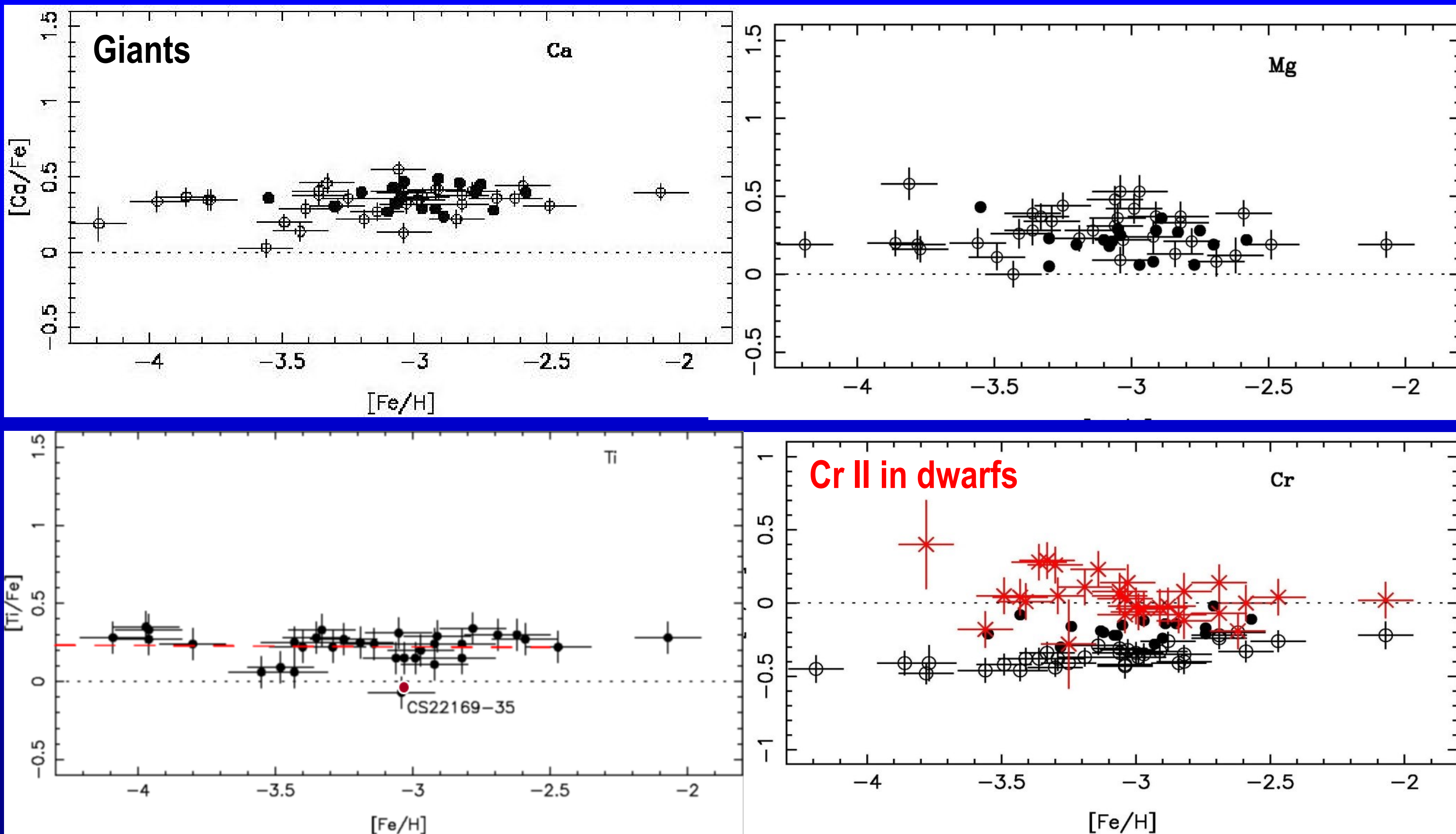
Standard chemical evolution models assume that heavier elements were first made from pure H and He in the first SNe II and efficiently returned to the local ISM. Low-mass *extremely metal-poor* (EMP; [Fe/H] ≤ ~ –3) halo stars were then born in GMCs seeded with the elements produced by the first stellar generation(s). SNe Ia later contributed to the evolution of the Milky Way halo and disk, at higher [Fe/H].

Observational check:

Precise abundance ratios ([X/Fe]) of normal, single EMP stars; the precise general trends define the main classes of outliers.

Result: Early (halo) ISM was *generally* very well mixed.

Establishing the 'Normal' Pop. II Pattern



Element pattern O → Fe group extremely uniform, but NLTE, 3D convection!

What Are the Main "Outliers"?

C-enhanced EMP (CEMP) stars:

[C/Fe] = 0.7 → 2+ dex; 20 - ≥70% of EMP giants

May or may not also show enhanced *s and/*or *r* elements

R-process enhanced stars (EMP-*r* stars):

[*r*/Fe] = 0.3 → ~2 dex; ~3% of EMP giants in MW t*oday*

(But *some* stars have [*r*/Fe] < 0; e.g. HD122563)

Problem: Spectra are complex, crowded, and non-standard.

Question: What are the outliers trying to tells us?

Question: Local or Global Enrichment?

Basically just **two** explanations of these excesses:

- They are only a surface effect, produced locally; ***or***
- The parent ISM clouds had already got this composition

Local production site(s):

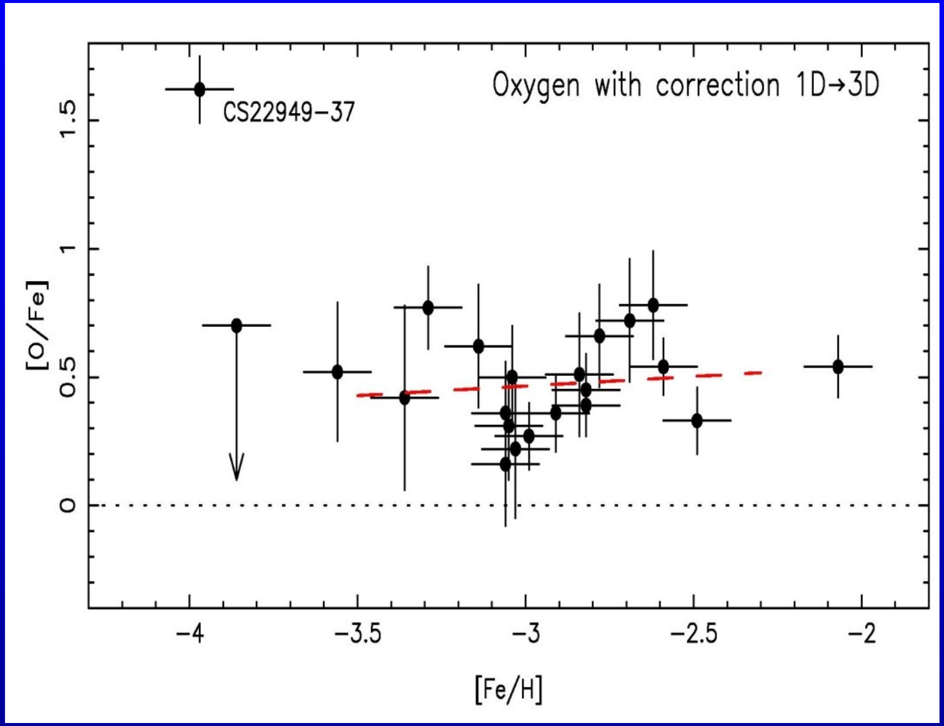
- Production, diffusion or mixing **within** the star itself, or
- **Transfer** of processed matter from a binary companion

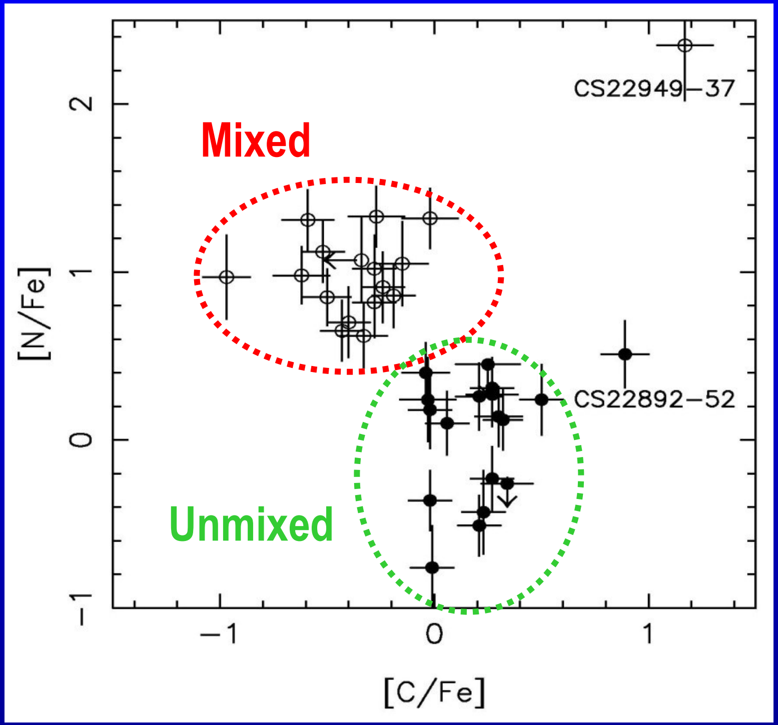
External production sites:

- Pollution of the parent cloud from a distant production site

Clue: *Frequency and orbits* of binaries in sample!

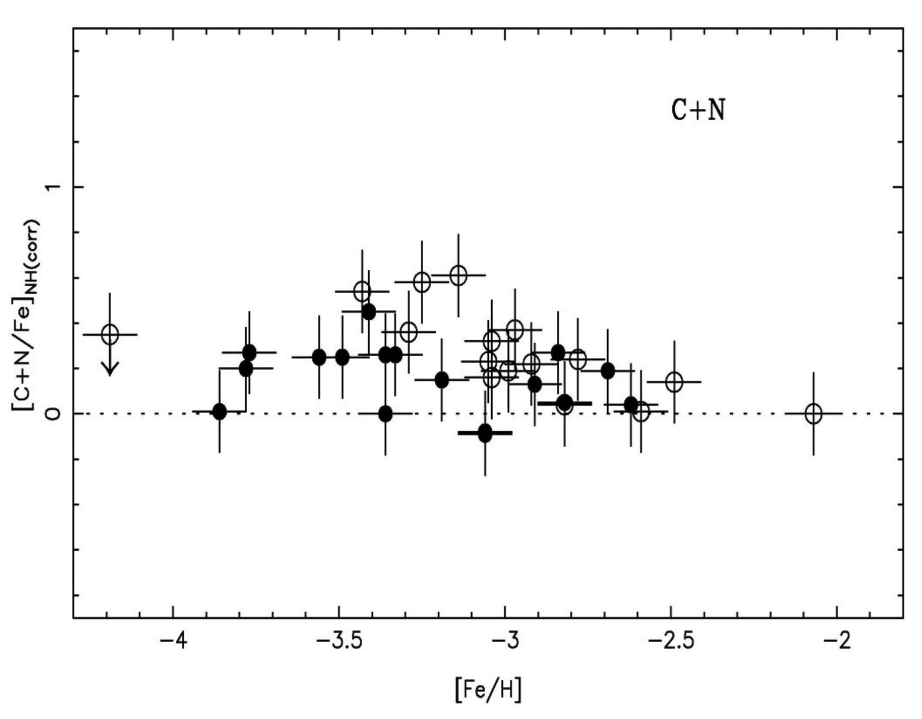
Is the Scatter of Local Origin?

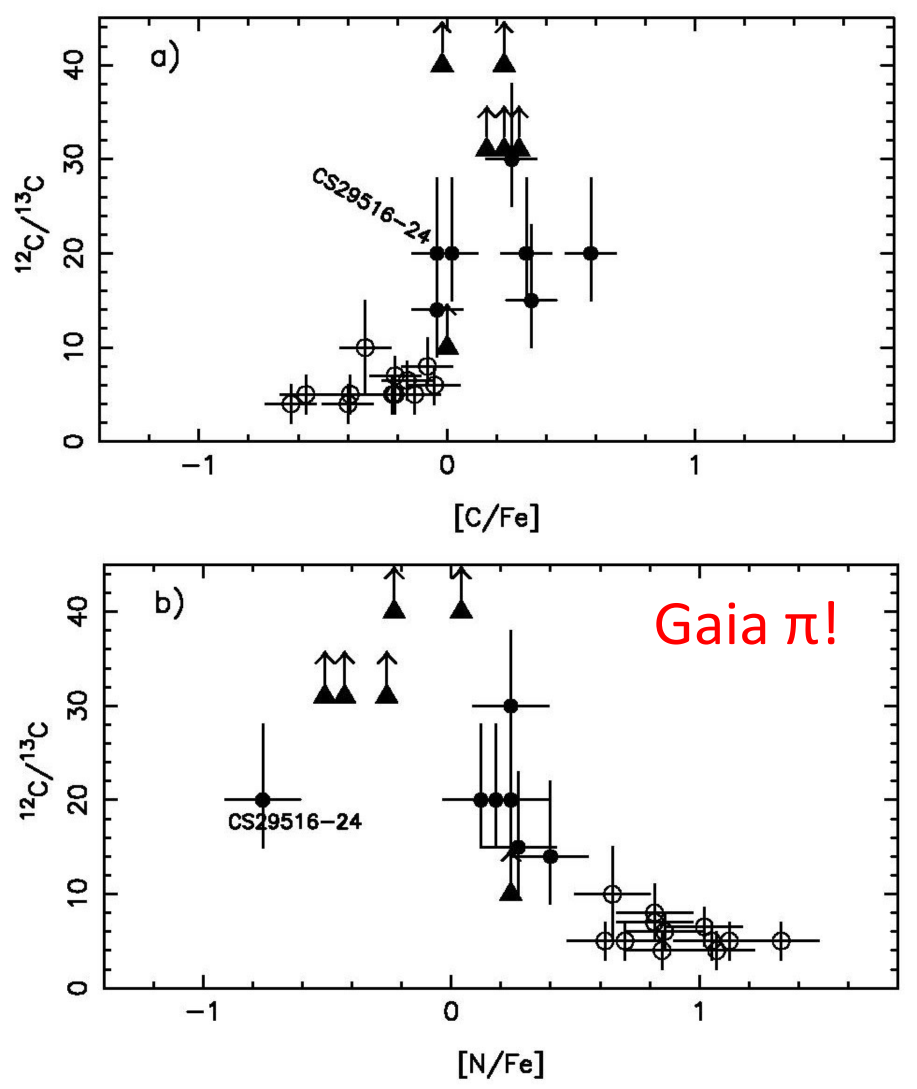




O behaves much better ?   C/N: mixing with CNO cycle!

Origin of the Scatter in C & N ?





Li and $^{12}C/^{13}C$ confirm that deep mixing occurred: CNO cycling just turned C into N (Spite+ 2005, 2006)

What Was Thought Before 2006?

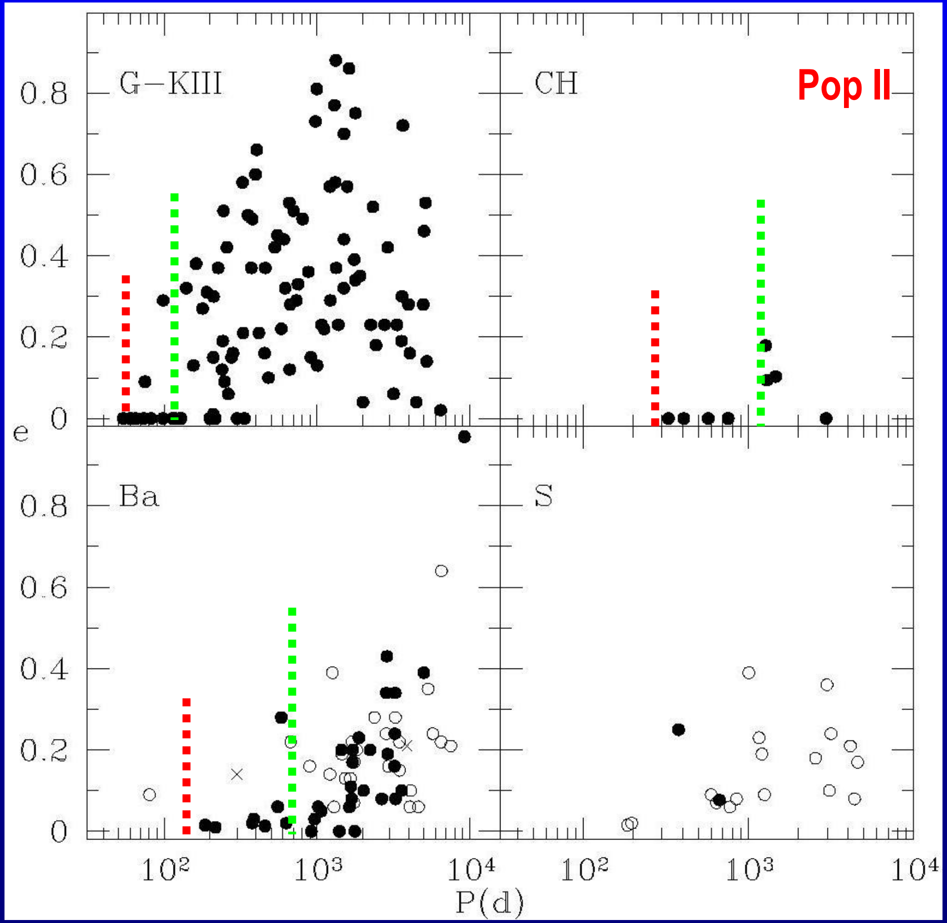
Conventional wisdom:
All chemical peculiarities were ascribed to binary evolution

Origin of EMP-r stars:
Original primary star became a SN II; polluted companion

Origin of CEMP stars:
Original primary star became an AGB star; polluted companion

Precise observational clues needed:
Reliable binary frequencies; orbital periods & eccentricities

Paradigm: C and Ba+s Were Transferred From a Former AGB Binary Companion



(Jorissen et al. 1998)

Note cutoff periods for:

common-envelope evolution (secondary R)

circularisation of orbits (Pop I: Depends on age)

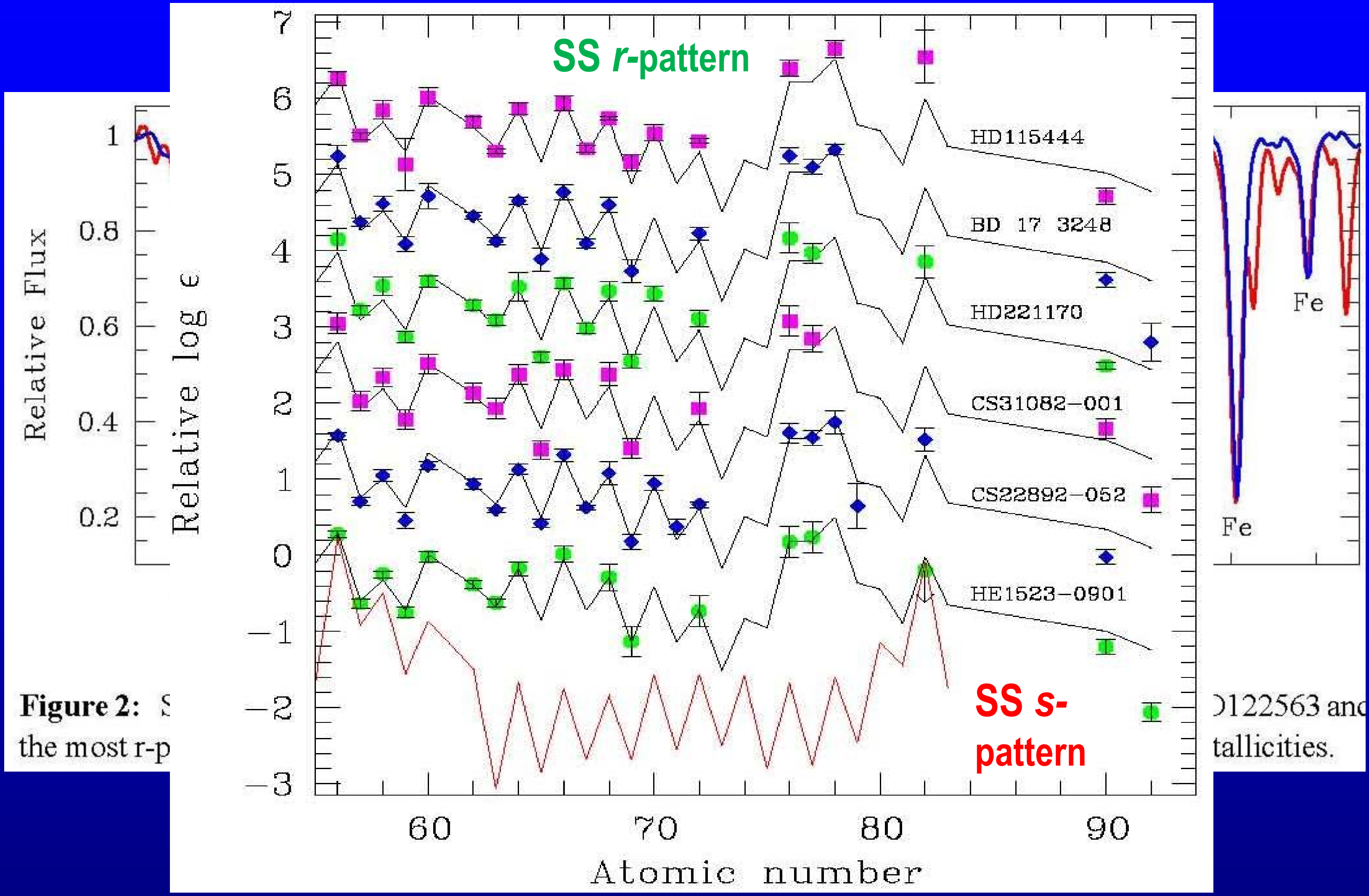
Theoreticians happy ☺

The Key Role of Accurate RVs: FIES@NOT is the Ideal Tool!

FIES spectra:

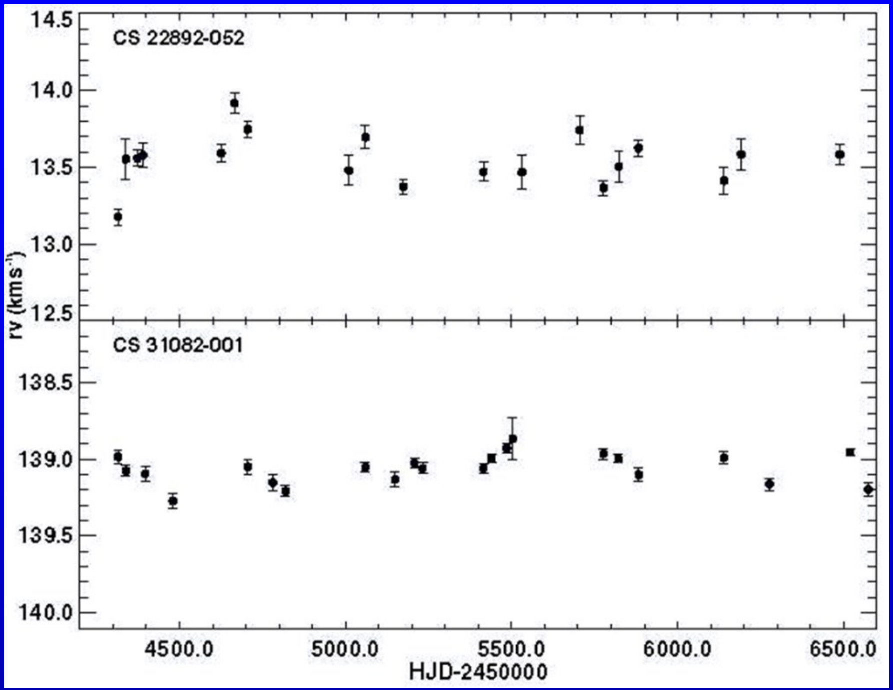
2.5-m telescope
(not 8-m VLT!)
Échelle format
R ~ 45,000
Underground vault
Stationary, stable T
Low S/N spectra
RVs: X-correlation
~ Monthly cadence
$\sigma \sim 100\ m\ s^{-1}$
Observe for ~8 yr...

First: The EMP-*r* (*r*-II) Stars ([Fe/H] ~ –3.0)



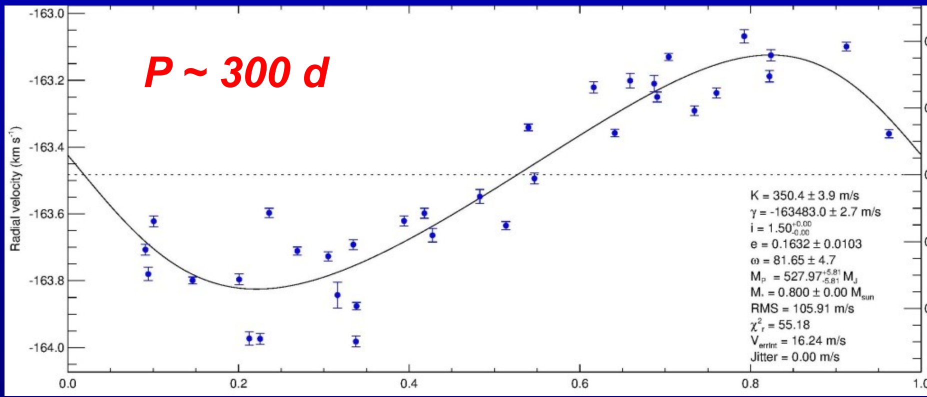
r-element pattern also extremely uniform, but offset by 0 - ~2 dex

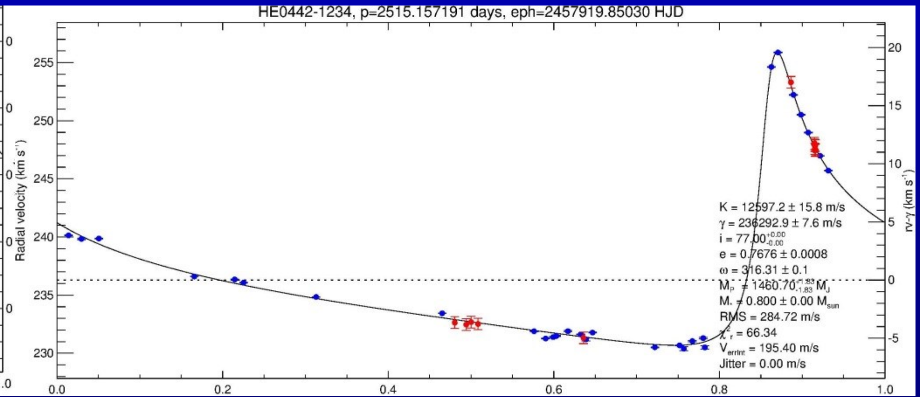
RV Monitoring With FIES@NOT (I)



Both the prototype *r*-II+CEMP star CS22892-052 and the C normal U star CS31082-001 are <u>*single*</u> (σ ≤ 100 m s $^{-1}$) – rare elements are irrelevant(!)

One U star has *K* ~ 350 m s $^{-1}$
One *r*-I star: *P* ~7 yr; *e* ~ 0.77





New: Leo II Most Giants are *r*-II!

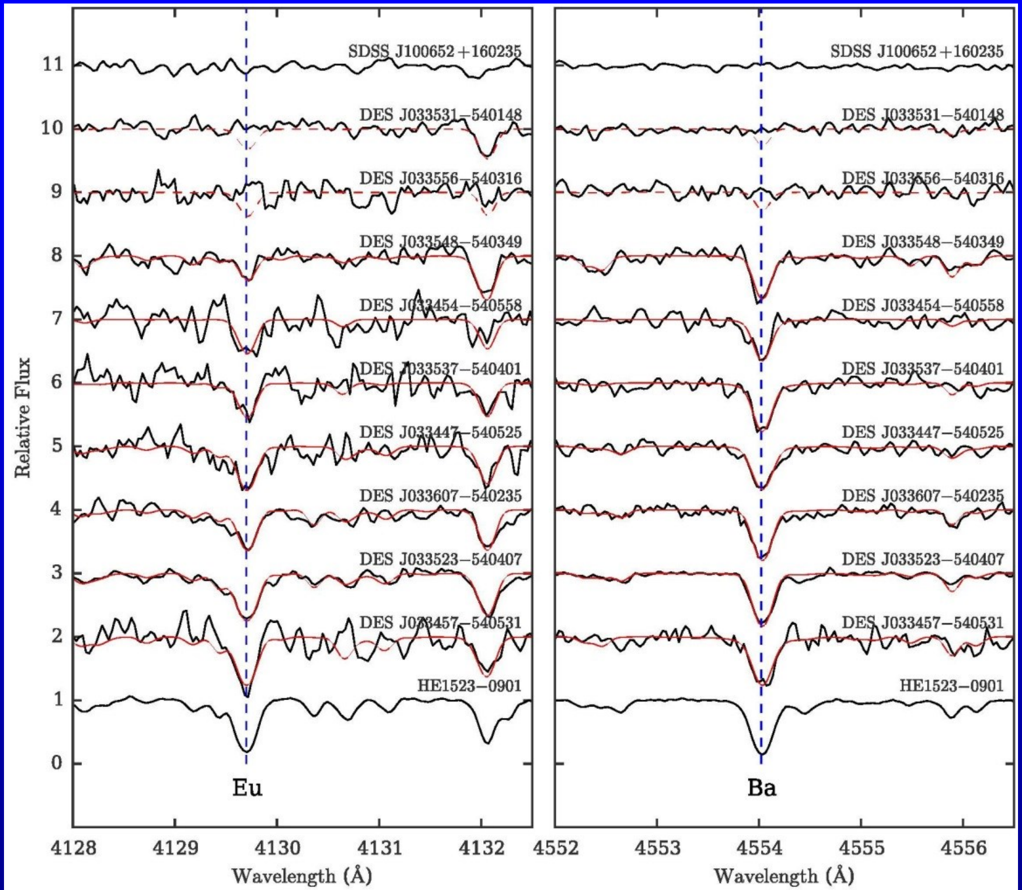


Figure 1: High-resolution spectra of Ret II stars around neutron-capture lines of Eu (412.9nm) and Ba (455.4nm).

Ji+ ***Nature*** 2015/6: 7 of 9 giants in UFD galaxy Leo II ([Fe/H] ≤ –3) are *r*-II stars ([*r*/Fe] ≥ 1.7)!

⇨ Most of galaxy ISM was likely enriched by a single *r*-process event (NS-NS binary merger or faint SN?)

⇨ Chemical enrichment is not simply local; rare elements just prove it!

New: CEMP Stars Are of Two kinds

CEMP-no Stars:

- No *s*-element signatures
- Most metal-poor group ([Fe/H] ≤ –3)
- Dominant group in outer halo
- Binary properties unknown

CEMP-s stars:

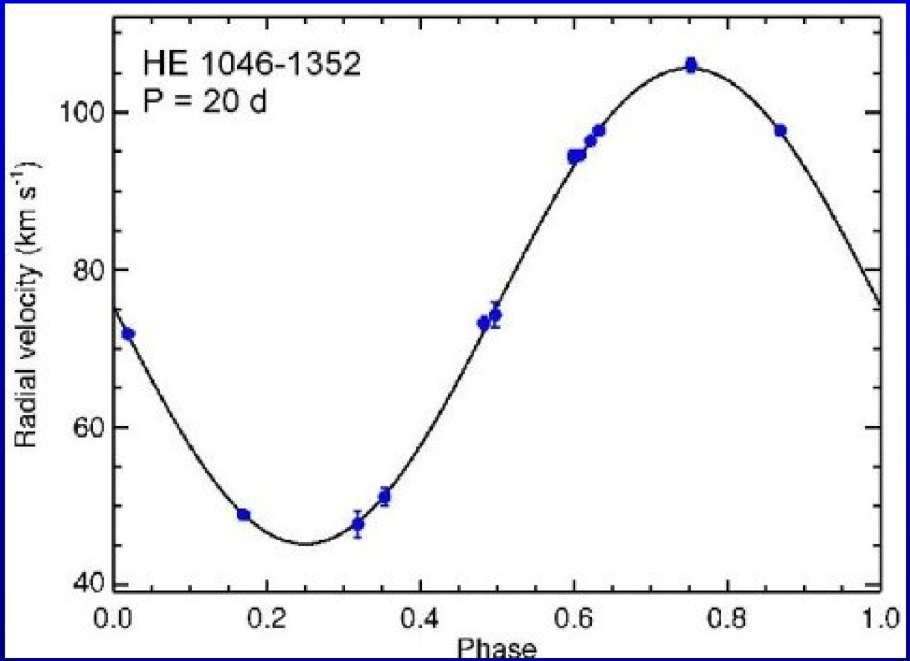
- Strong *s*-element signatures
- Dominate in inner halo
- Binary frequency high (+ simulations: 100%??)

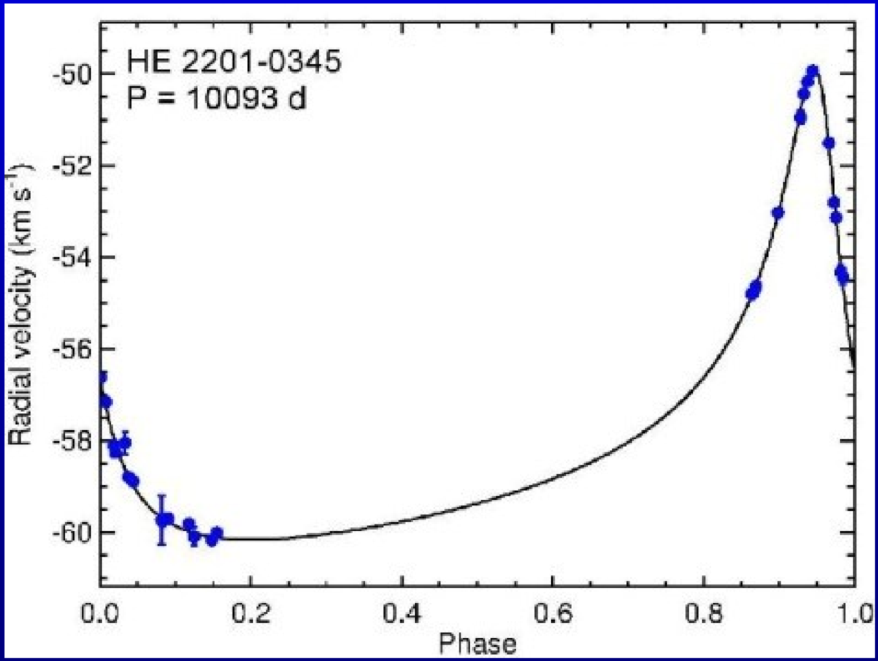
RV Monitoring of CEMP stars (II)

Most (≥80%) CEMP-*s* stars are indeed binaries, but CEMP-no and EMP-*r* stars are generally *single*. *Some* (~20%) CEMP-*s* stars are also single (σ < 100 m s^{-1}). 20-d binary has no space for AGB star!

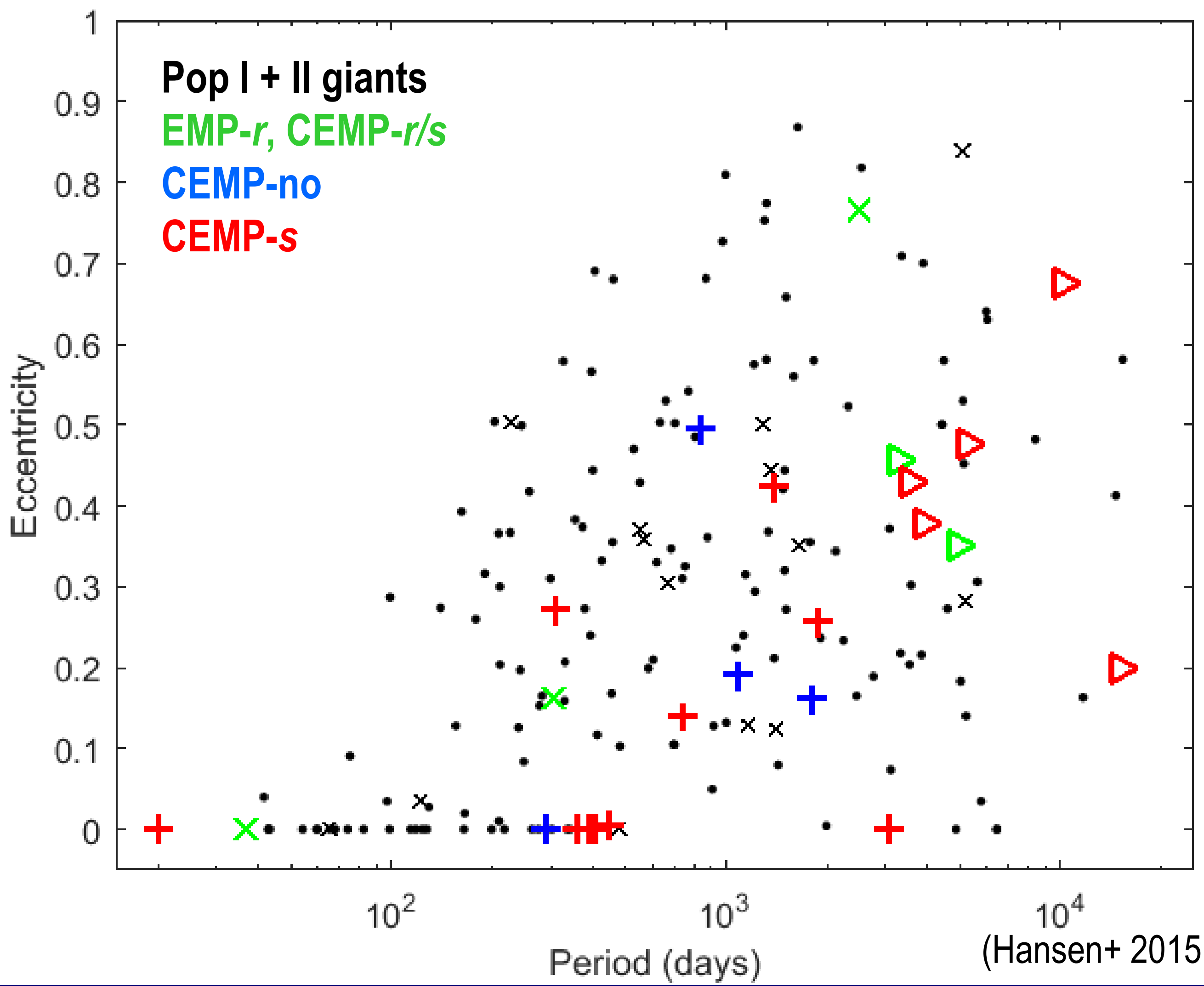
P = 20 d ('normal' or post common-envelope?)

P ~30 yr(!)





Summary of Binary Orbit Properties



(Hansen+ 2015,2016)

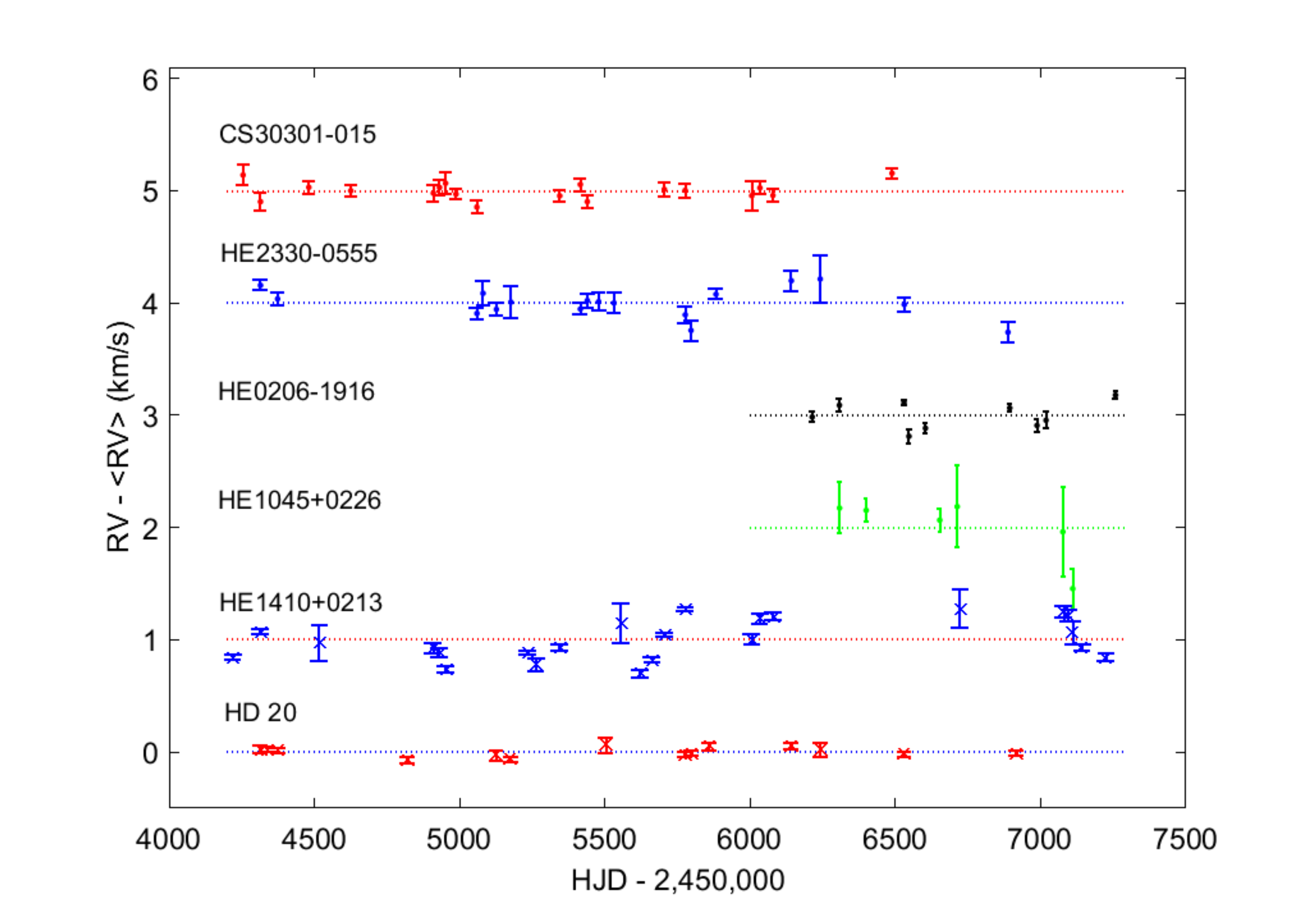
The Single Stars are Really Single!

- but some seem to <u>pulsate!</u>

- Distances
- Kinematics
- Evolution

- are unknown!

Are field stars Giants or AGB?



(Hansen+ 2016)

Answer in 2017: *Gaia* space astrometry & photometry!

Results/Conclusions:

- The CEMP-no and EMP-*r* stars are basically ***single***
- ~20% of the CEMP-*s* stars are also single(!)
- Most, *but not all* CEMP-*s* stars are in (long-period) binaries
- ⇨ Abundance anomalies are ***intrinsic*** and were imprinted on the parent clouds across interstellar space in ISM at $z \geq 3$(?)
- Early chemical enrichment was complex and *non-local*: New elements could form far from the natal clouds of EMP stars
- Could this process account for the C-rich DLAs at z = 2-3?
- What is origin of the C in the CEMP-no and single CEMP-*s*?
- Alternatives: ‘Faint’ SNe with fallback & mixing? Or ‘spinstars’?
- Some (single) CEMP stars seem to be *pulsating*; *Gaia* should tell!

THANK YOU !

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