Chemistry & Dynamics of the Milky Way – From Before Hipparcos Until Gaia

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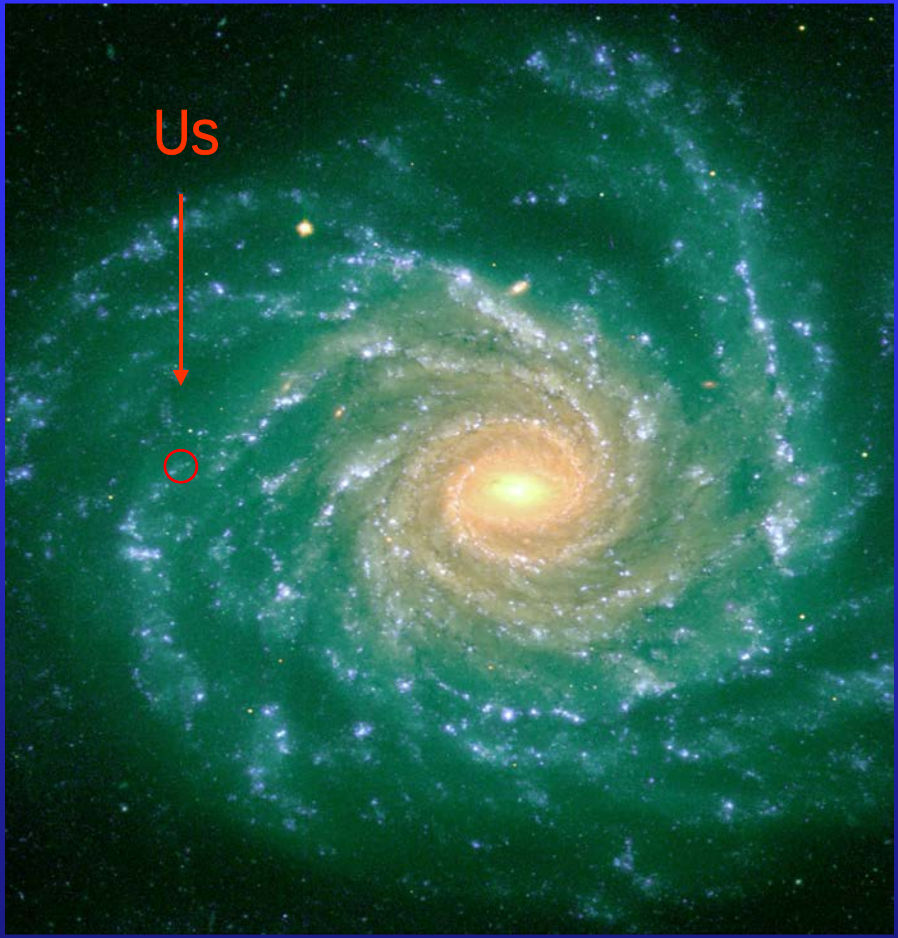
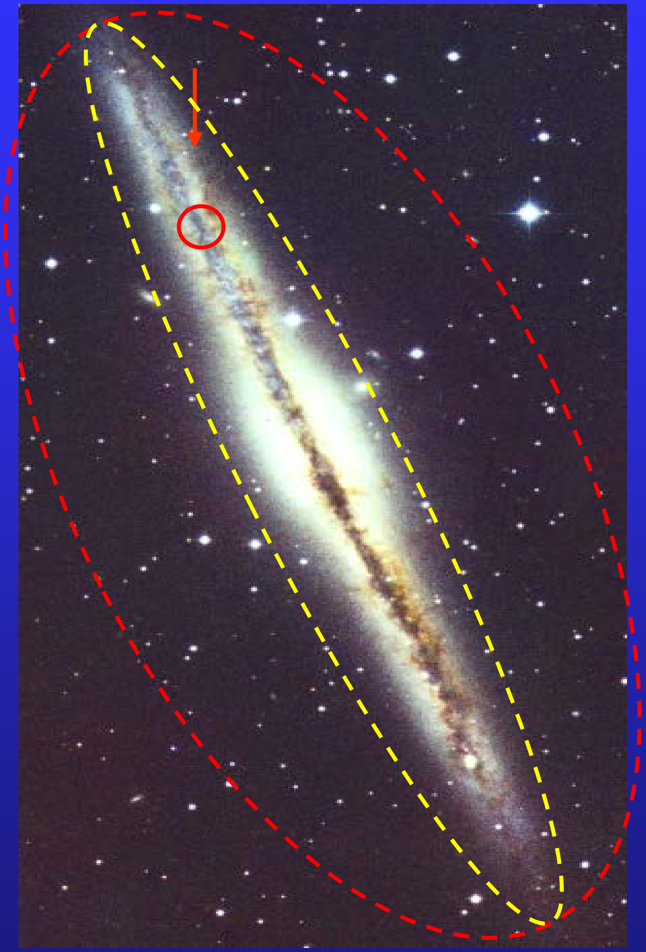
Dark Cosmology Centre

SAC
STELLAR ASTROPHYSICS CENTRE

The Milky Way: Our Prototype Disk Galaxy



NGC 1232



NGC 4565

Witnesses of the Evolution: Stars

- Detailed chemistry and motions of stars of all ages
- Disk probes: Solar-type dwarfs; Halo: Giants
- What parameters do we want to know?
  - Age; dwarfs (models, T_{eff}, log *g*, M_V ⇨ *uvby**β***)
  - Metallicity ([M/H] ~ [Fe/H]; [X/Fe])
  - Distances, reddening ⇨ **π**; *uvbyβ*
  - Space velocities U,V,W ⇨ **μ**, **π**, RV
  - Disk heating; Galactic orbits; inner/outer halo
- Main targets: Solar vicinity (disk life); extreme early halo

Rewinding History: The GCS Disk Survey

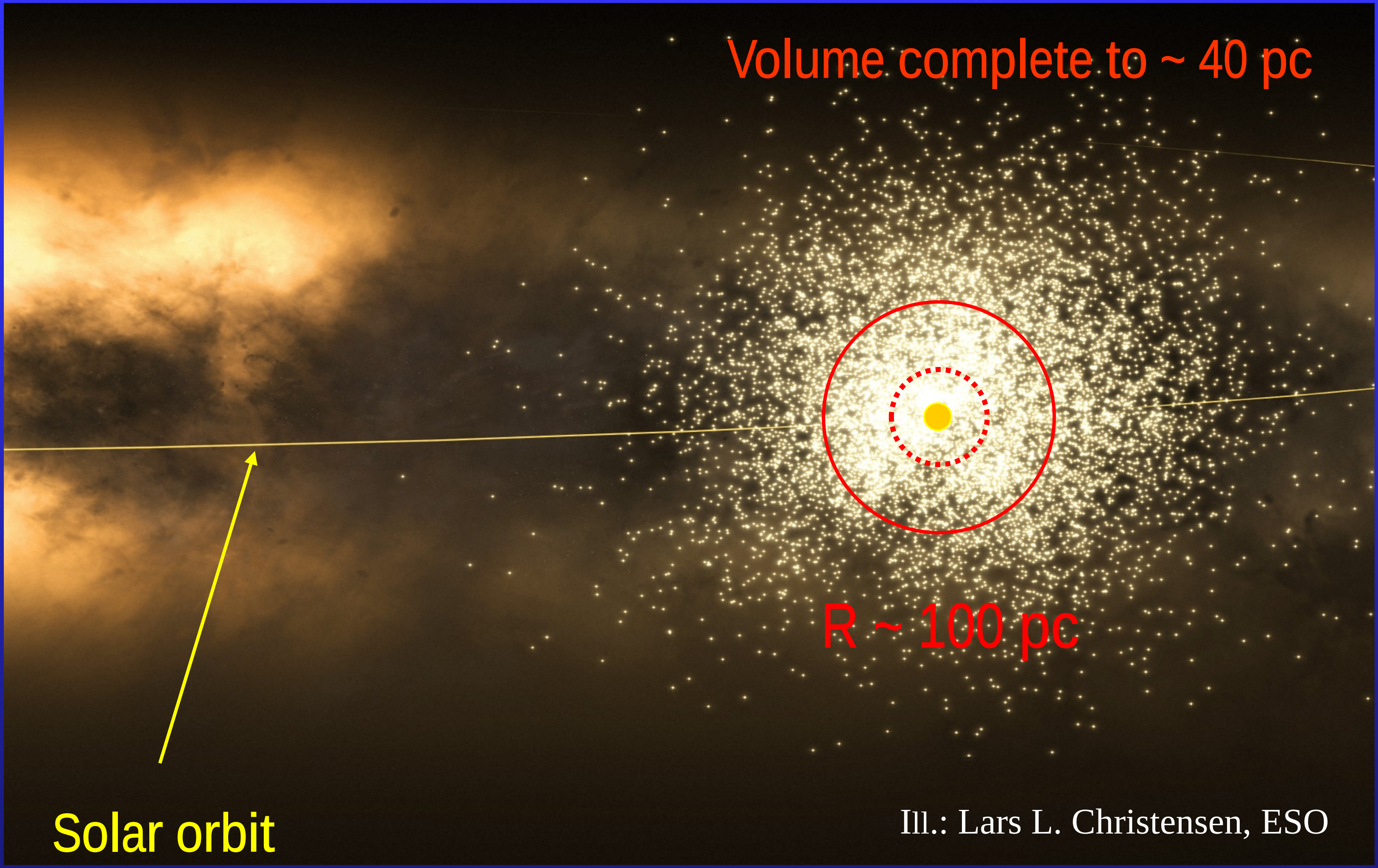
I: *uvbyβ* photometry of <u>all</u> ~30,000 A5-G stars in the HD to V $\approx$ 8.5
Apparent magnitude limited sample (E. H. Olsen 1975-1994)

II: Select <u>all</u> ~17,000 *bona fide* F & G dwarfs from stage I
Ages can be derived for stars 0.5-1.5 mag above ZAMS
When distances known, volume limited sample can be defined

III: Multiple RV observations of (nearly) all stars from stage II
(~63,000 new obs. of 14,139 stars - ~1,000 observing nights @ ESO + OHP + CfA; Geneva-Copenhagen team 1981 – 1997)

IV: Re-check and complete all data (Hipparcos!); revisit calibrations
(Re)compute distances, velocities, [M/H], ages, Galactic orbits
(Lund – Copenhagen – Geneva 2003 – 2009)

The GCS Disk Sample; Completeness



Preparation: Test the Stellar Models

Key questions for ages at start:

- Opacities; core convection; overshooting

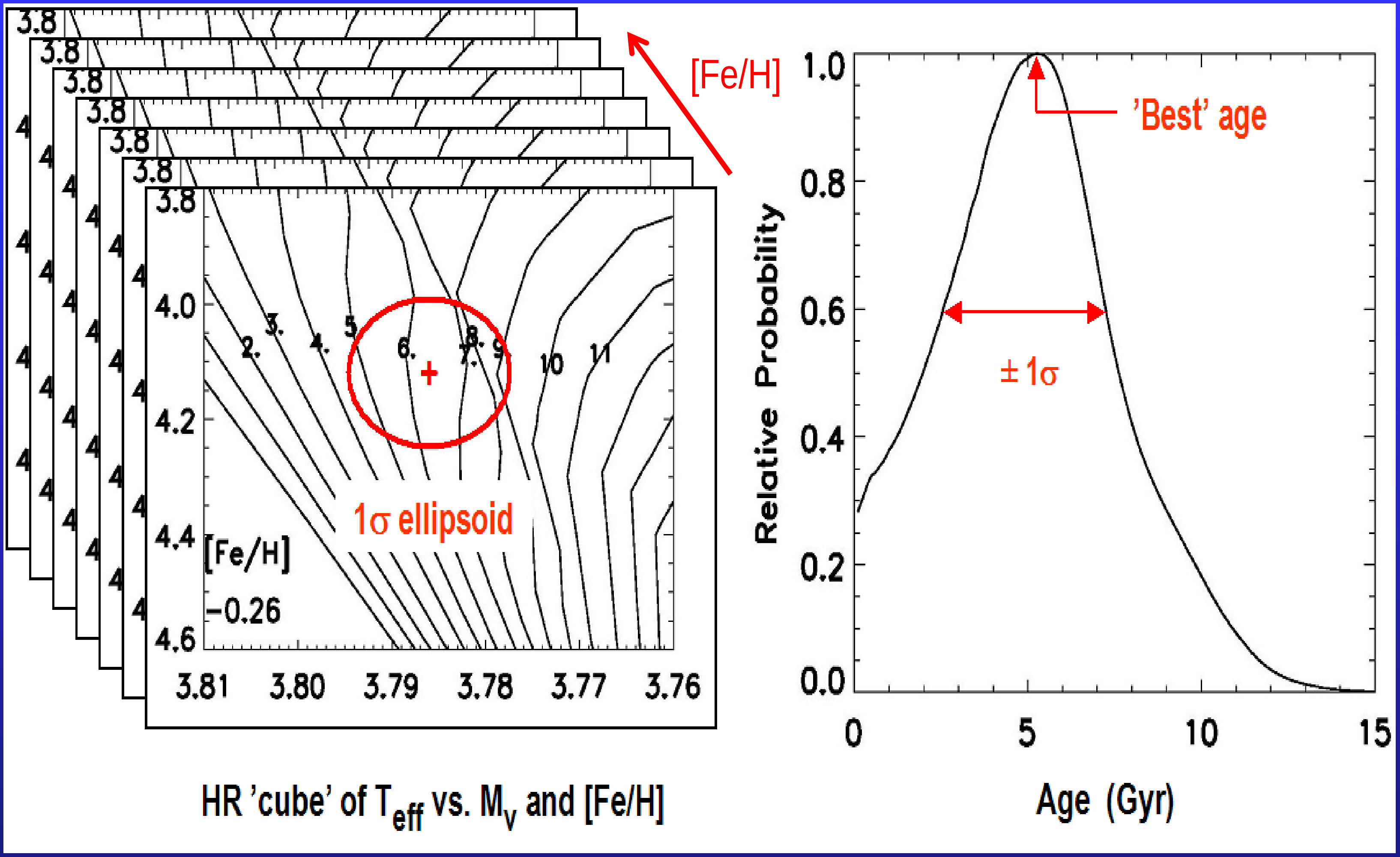
Test objects 1: Detached double-lined eclipsing binaries

- Complete, accurate, *uvby* light curves
- Spectroscopic orbits (1.52m spectra, CORAVEL, +…)
- [Fe/H] ([M/H] from *uvby****β***; [X/Fe] from CES, McD, …)

Test objects 2: Open clusters with ages 1-4 Gyr

- Accurate *uvby* colour-magnitude diagrams
- RV identification of non-members and (binary) members

Method for Calculating Ages and Errors



Adjust Teff scale as needed to match observed ZAMS @ low [Fe/H]

MDF and Age-Metallicity Relation

1010 B. Nordström et al.: The Geneva-Copenhagen survey of the Solar neighbourhood

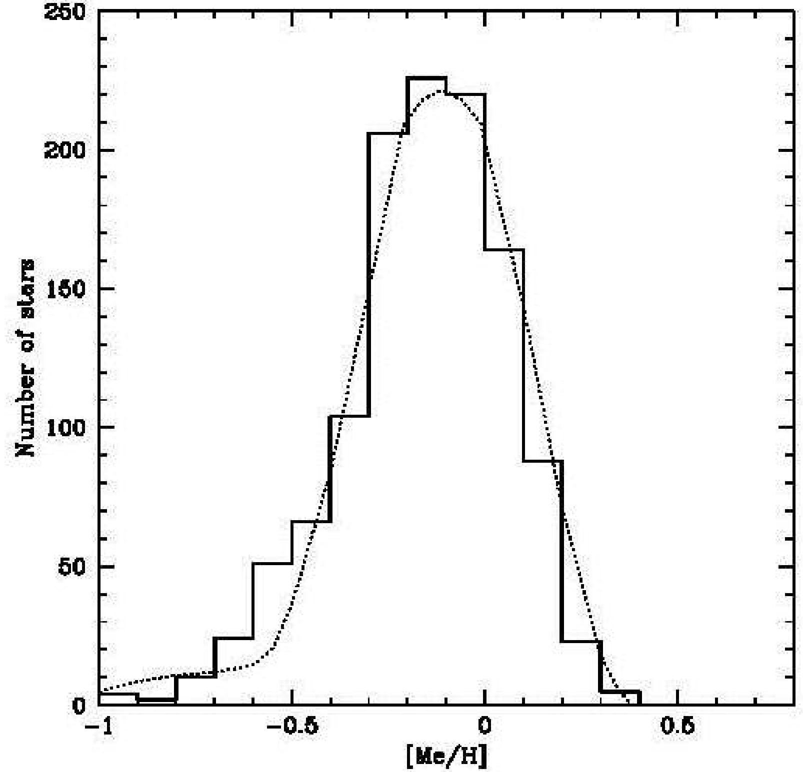


Fig. 26. Distribution of metallicities for the volume complete sample of single stars (full histogram). For comparison the dotted curve shows the reconstructed distribution for G dwarfs from Jørgensen (2000), which is corrected for scale height effects and measurement errors.

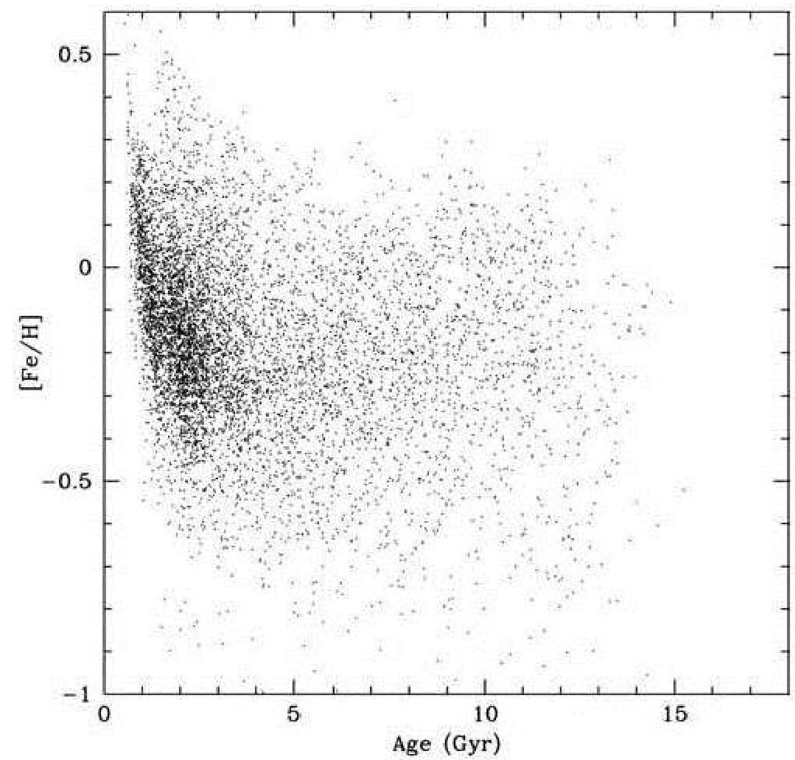
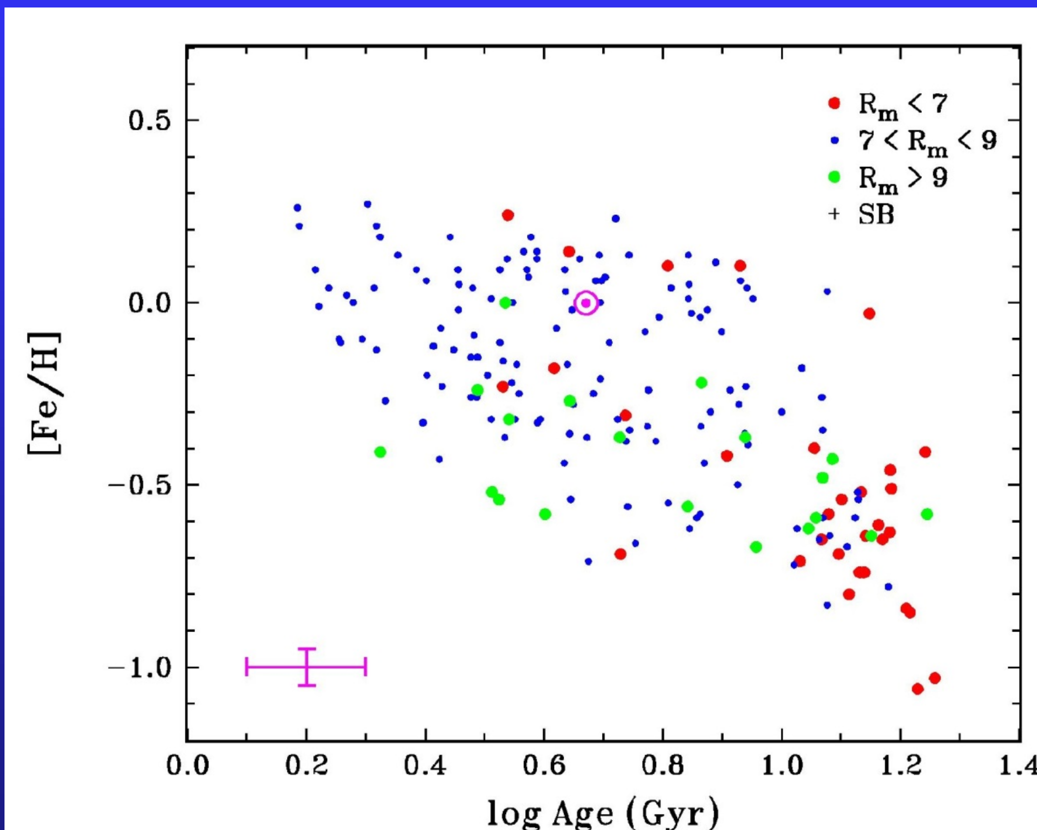


Fig. 27. Age–metallicity diagram for 7566 single stars with "well-defined" ages in the magnitude-limited sample. Note that individual age errors may still exceed 50% (cf. Fig. 16).

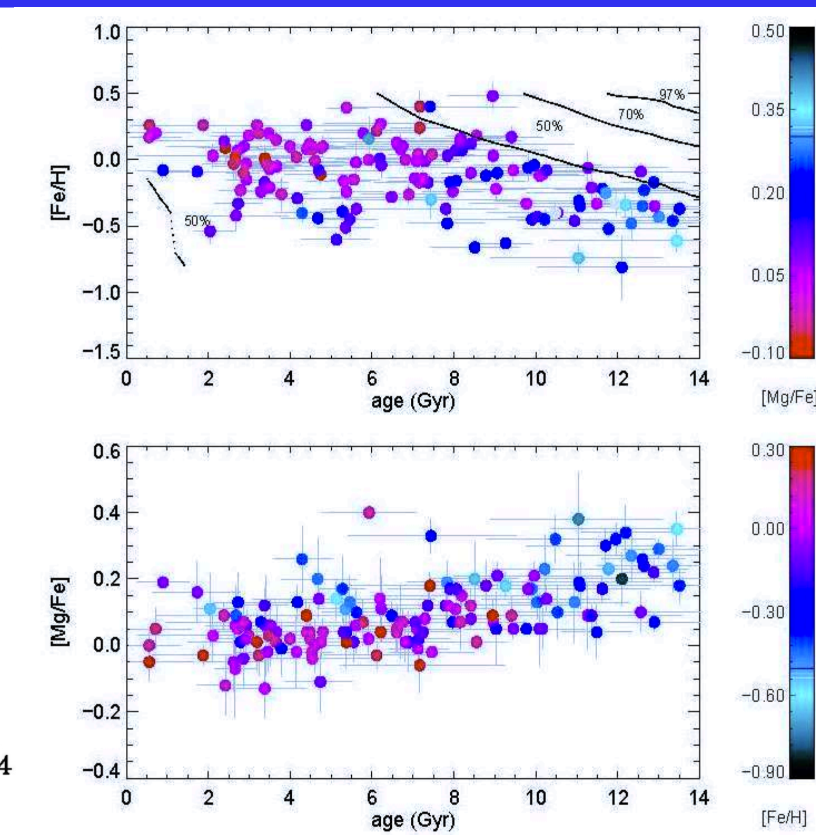
"G dwarf problem" and closed-box chemical evolution

AMR: Evolution Over 20 Years…

Edvardsson et al. (1993)

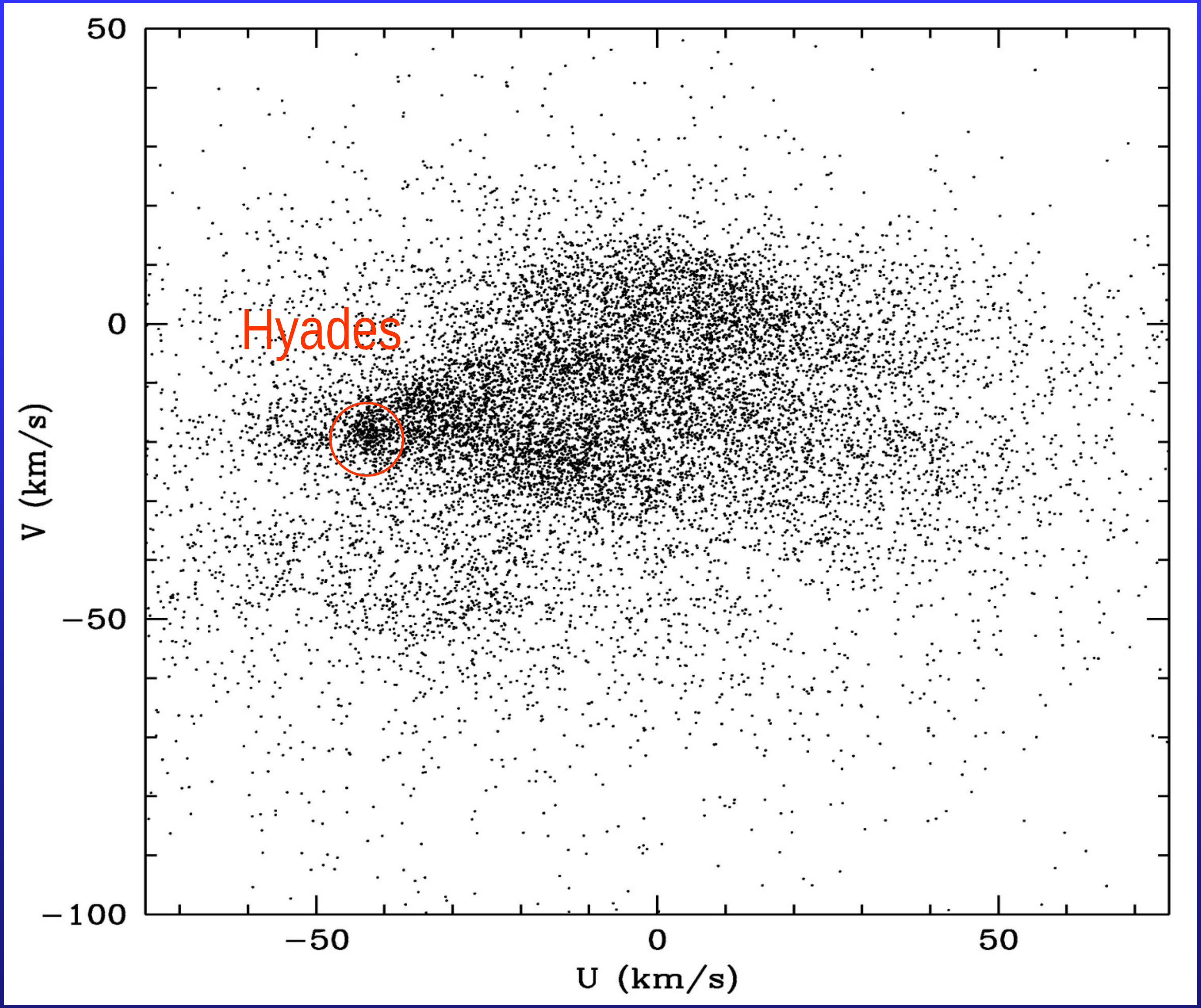


Gaia-ESO Survey (2014)



- Same selection effects…

The U-V Plane: Not Two Gaussians!

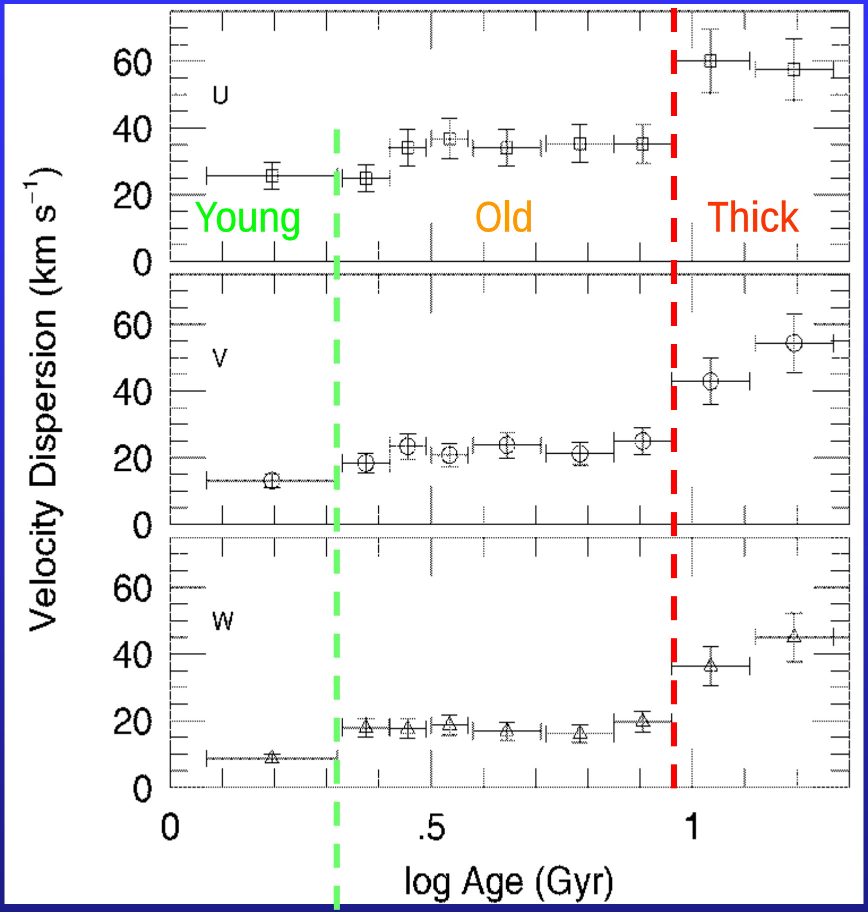


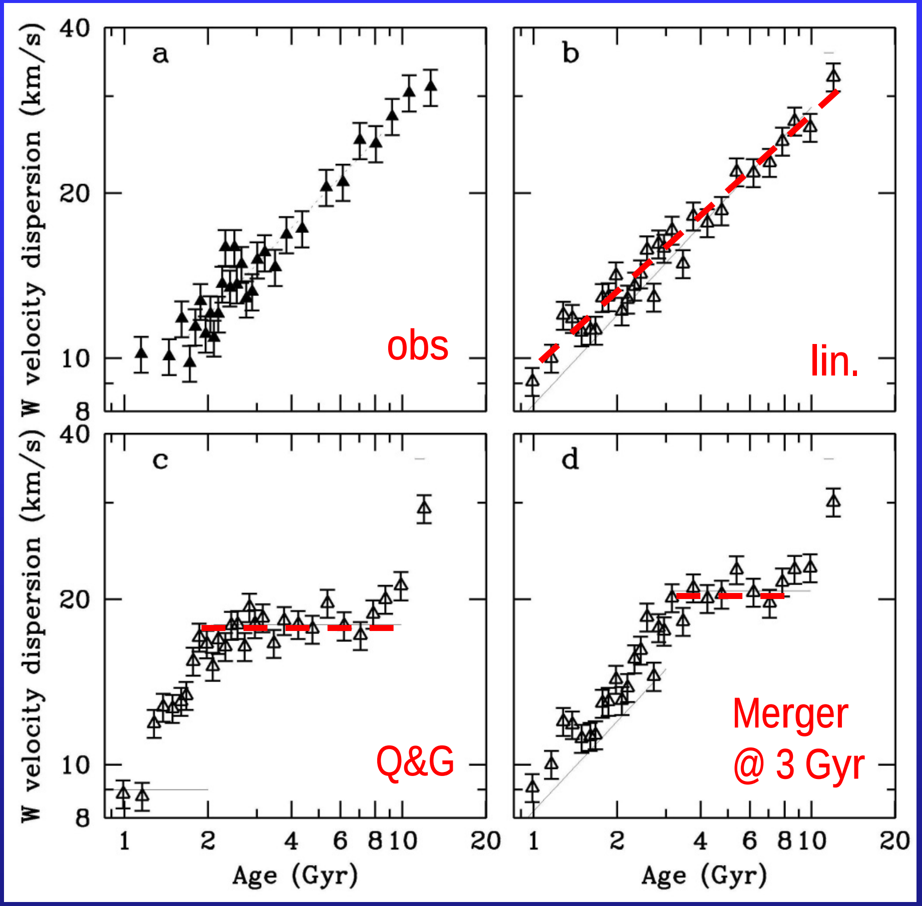
Not thin + thick disk!

Dynamical focusing?

Radial migration?

Disk Heating: Models vs. Reality





Quillen & Garnett 2001:
189 dwarfs from Edv '93

GCS III: 2,626 single stars,
σ_{Π} < 13%; σ_{Age} < 25%

GCS I-III Finally Published 2004-2009

A&A 418, 989–1019 (2004)
DOI: 10.1051/0004-6361:20035959

Astronomy & Astrophysics

The Geneva-Copenhagen survey of the Solar neighbourhood⋆,⋆⋆

Ages, metallicities, and kinematic properties of ∼14 000 F and G dwarfs

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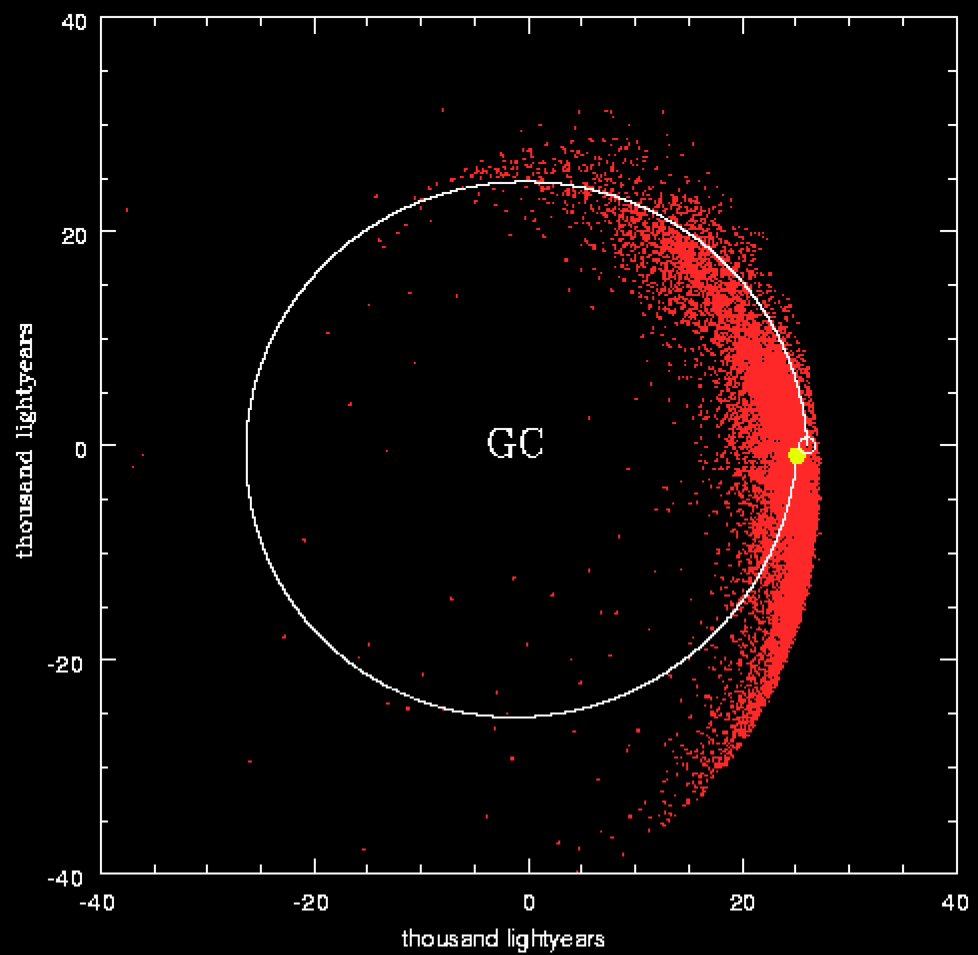
Set a deadline…!

Now ~1,600 cit. total

“The GCS Movie”



”Solar neighbourhood”??

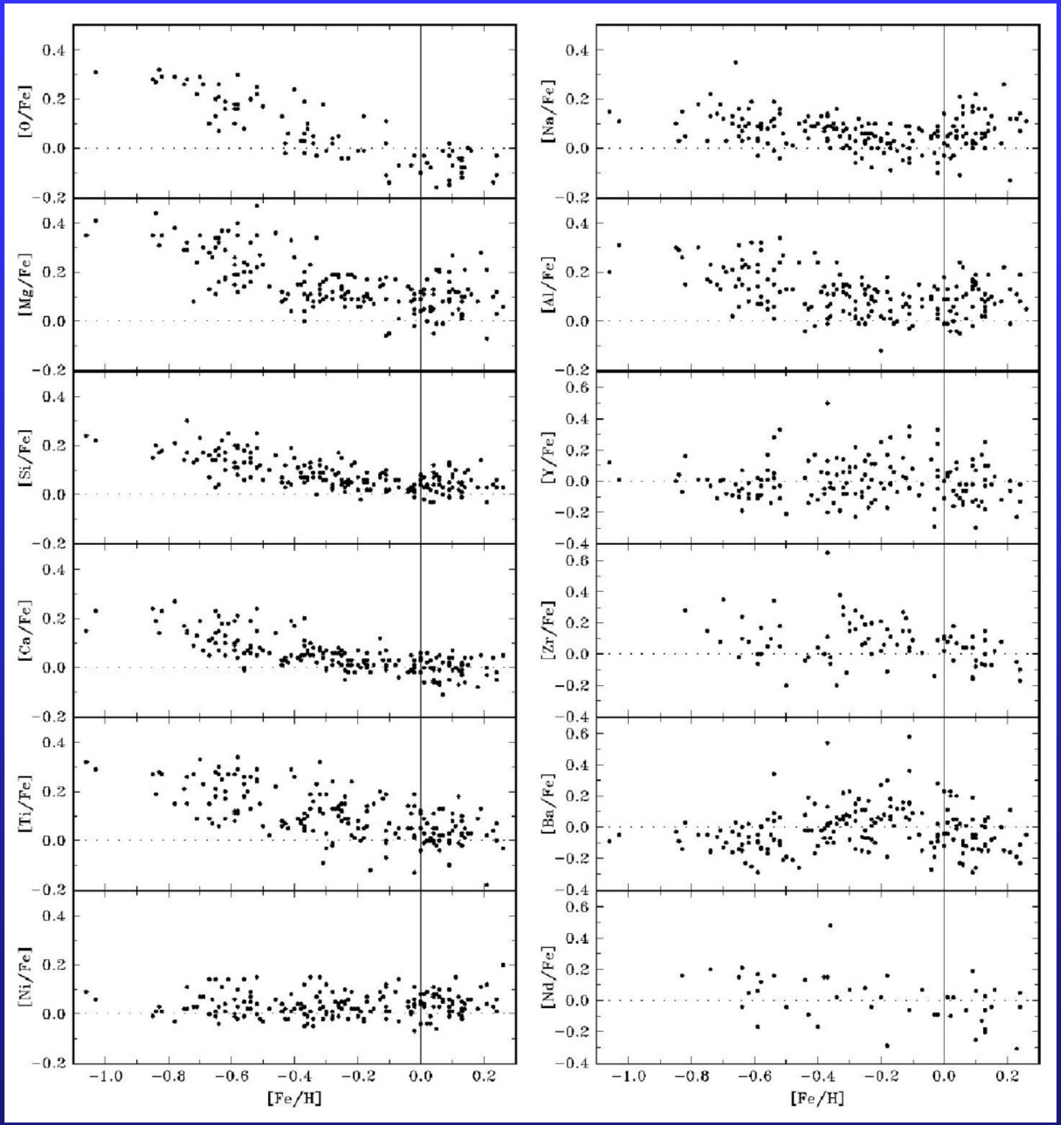
A Subset: Detailed Element Abundances

- What stars made which elements, how, where, and when?
  - Test the best atmospheres & synthetic spectra
  - Instrument (CES) designed to obtain <u>*accurate*</u> spectra

First visitor run
December 1981

- a young
David Lambert

Disk: Evolution of Element Abundances



Subsample of 189 FG dwarfs

Edvardsson et al. (1993)

Now 1,650 cit

General: Galactic Chemical Evolution

From the Big Bang via the Solar System to Today

Conventional picture:

Pop. III stars were presumably massive, exploded as SN II, and efficiently returned new heavy elements to the ISM. This enabled lower-mass extremely metal-poor (EMP) halo stars with [Fe/H] ≤ ~ –3 to form in GMCs seeded with these elements). Later SNe II and eventually SNe Ia further boosted the chemical evolution of the Milky Way halo and disk at steadily higher [Fe/H]. Outliers were 'just' due to binaries….

Observational check:

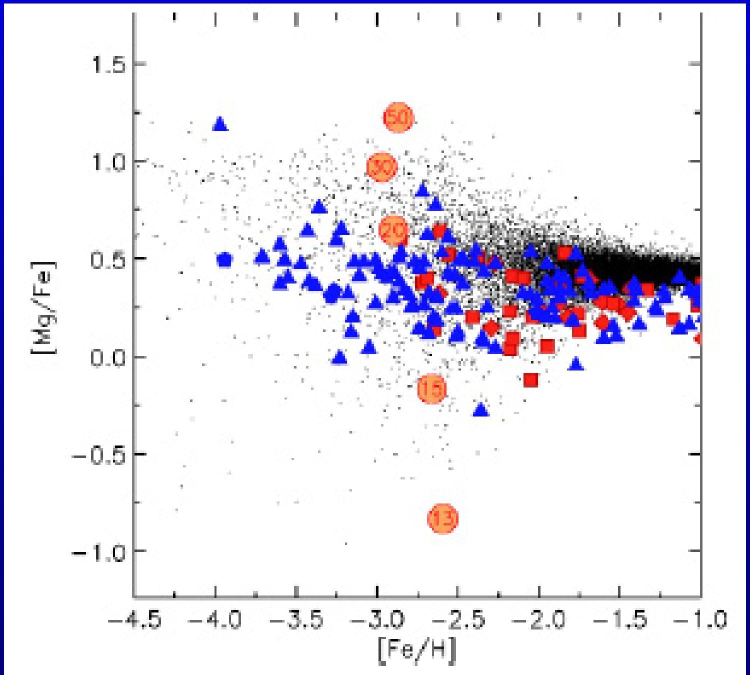
Precise ([X/Fe]) ratios of normal (Pop I +) Pop II stars ("Edv+ for the halo")

Stochastic Early Halo Enrichment ...?

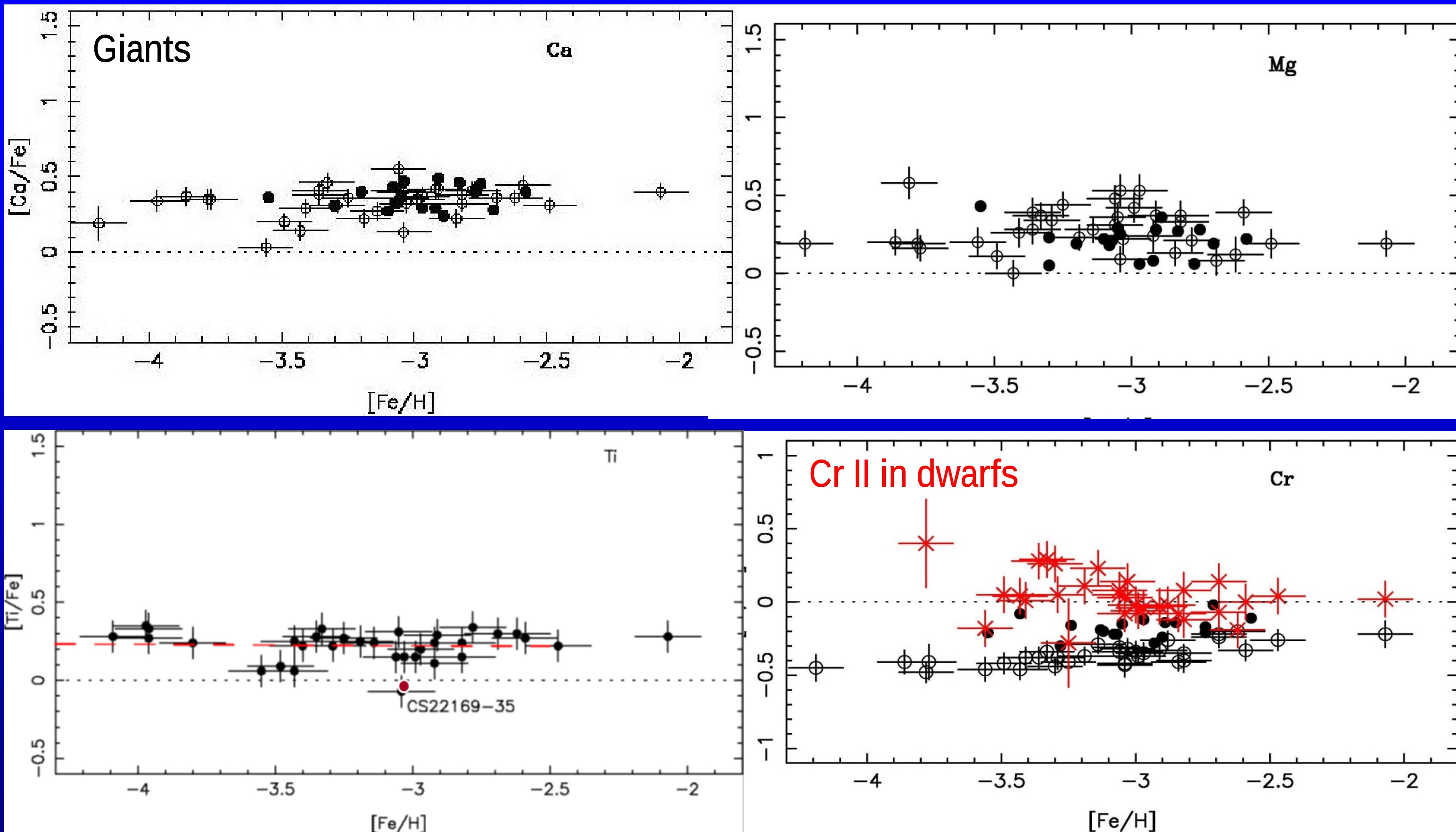
Conventional Wisdom:
Stochastic chemical evolution models produce significant dispersion in EMP element ratios (e.g. [Mg/Fe]).

Observational Reality:
Precise observed [Mg/Fe] relations
△ are tighter than models predict.

⇨ <u>Very</u> accurate observations
are needed: ⇨ UVES@VLT!

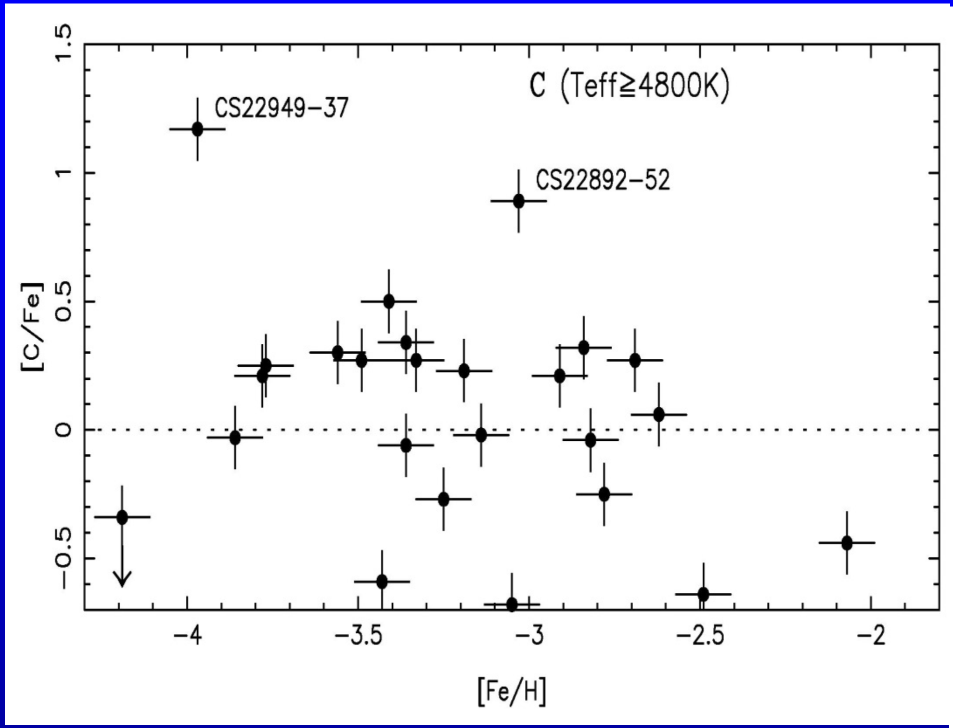


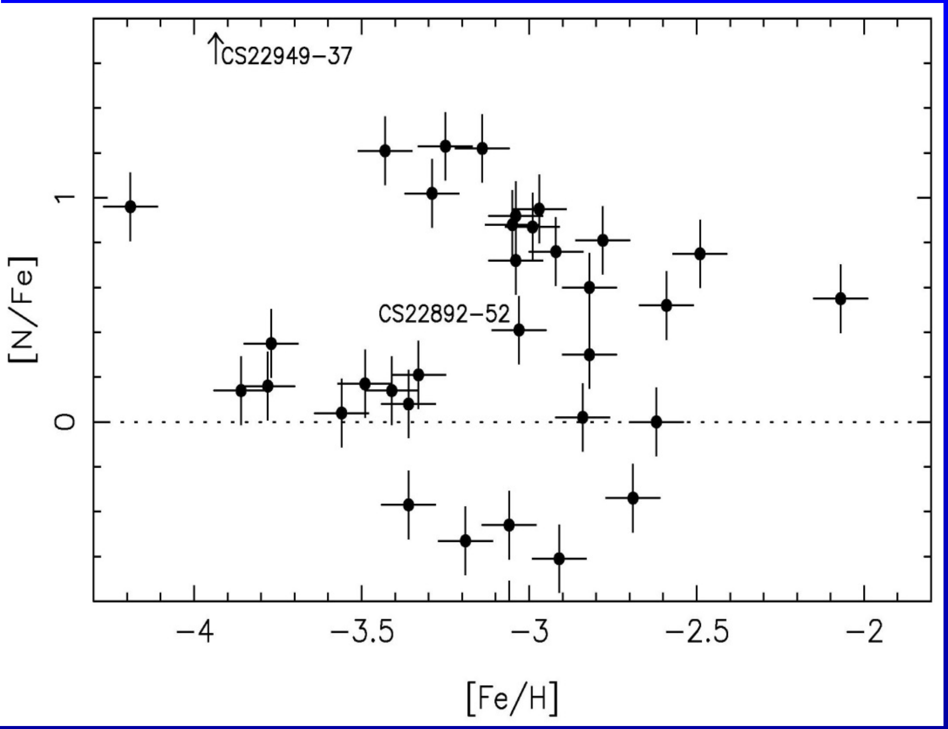
“First Stars”: The ‘Normal’ Pop. II Pattern



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

The First Elements Produced: CNO



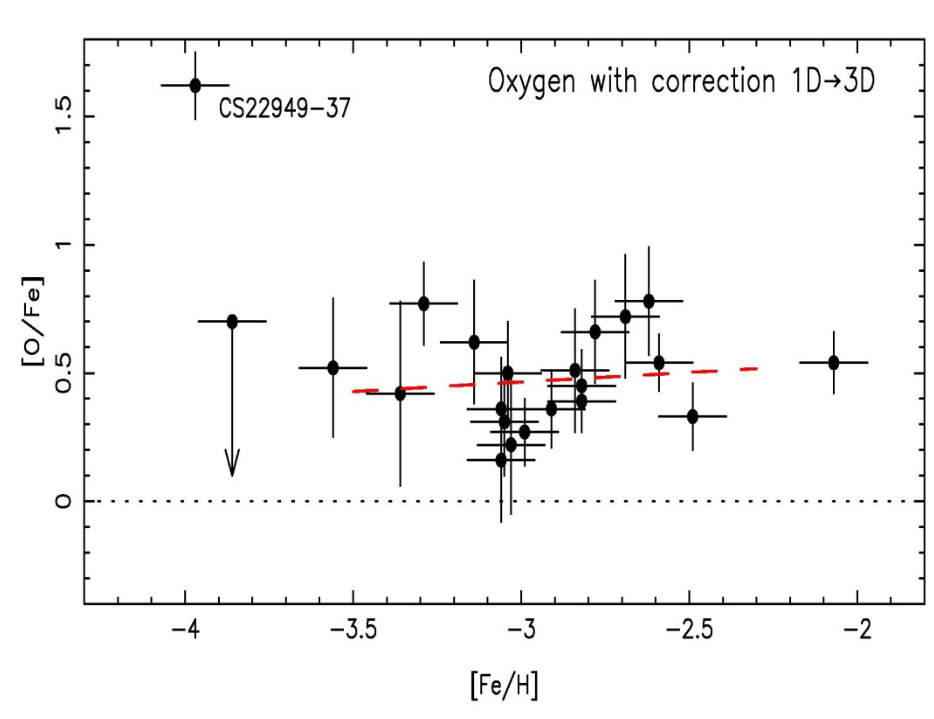


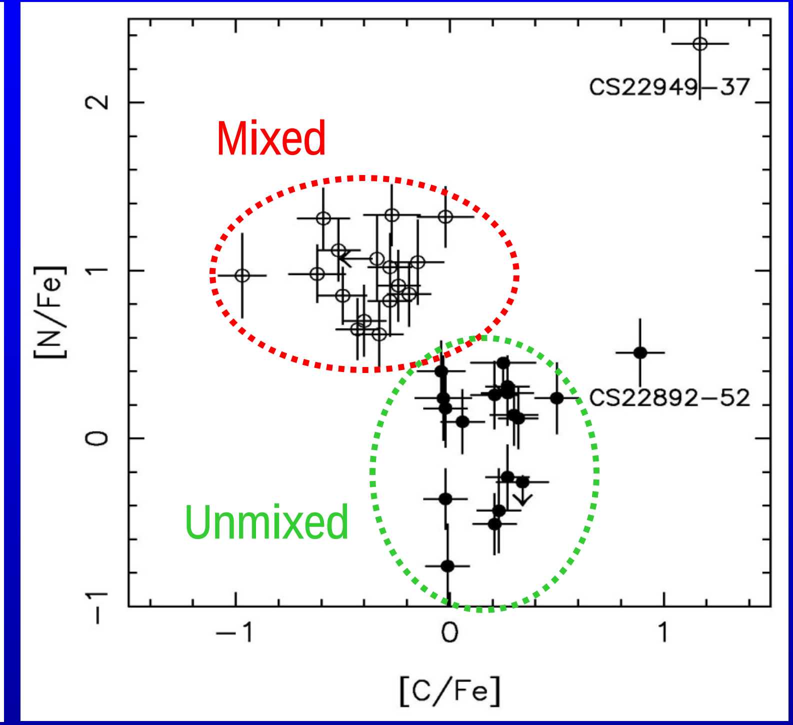
C from CH band @ 430 nm

N from NH band @ 336 nm

Why is the scatter in C and N so enormous?? SNe II should be simple! Is this intrinsic or caused by internal processing?

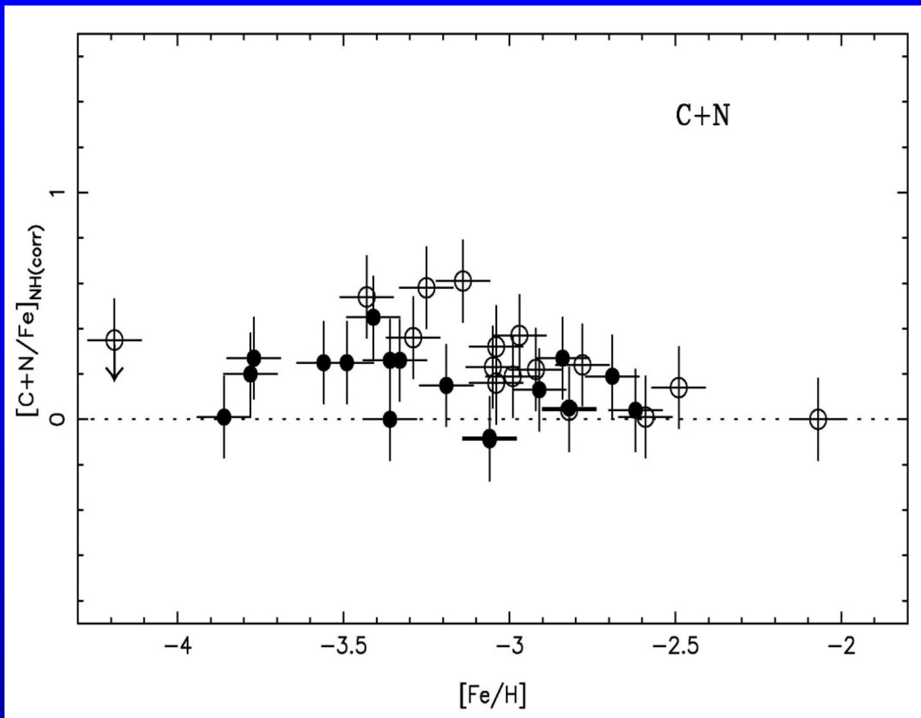
Origin of the scatter in C & N ?

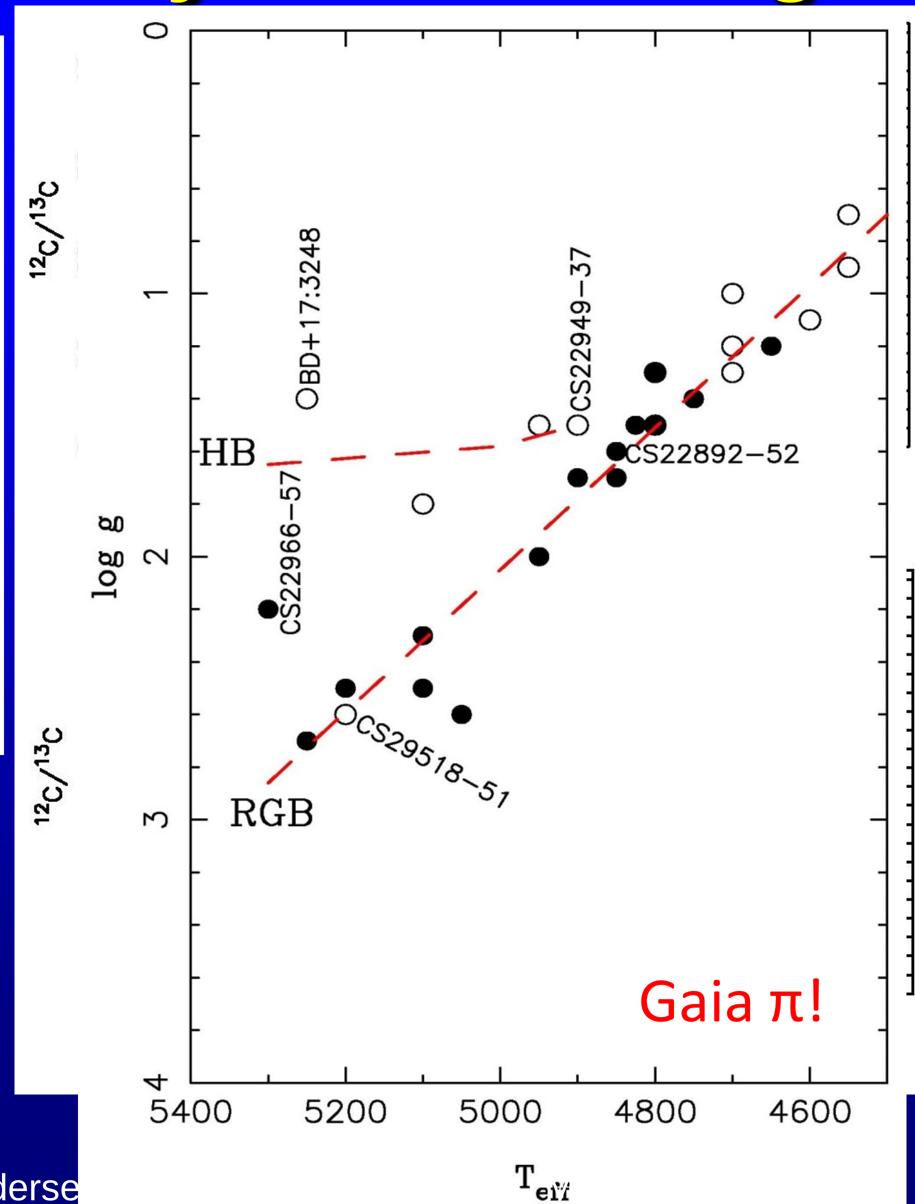




O behaves much better ?   C/N: mixing with CNO cycle!

Explanation: CNO Cycle + Mixing!





Li confirms the deep mixing

- and the $^{12}C/^{13}C$ ratio as well

CNO cycle just turned C into N

What True Chemical Peculiarities are Prominent in Today's EMP Stars?

C-enhanced EMP (CEMP) stars:

[C/Fe] = 0.7 $\rightarrow$ 2+ dex; 20 - $\geq$70% of EMP giants

May - or may not - also show enhanced [*r,s*/Fe]

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

[*r*/Fe] = 0.3 $\rightarrow$ ~2 dex; rare: ~3% of EMP giants

S*ome* stars also have [*r*/Fe] < 0 (e.g. HD122563)

NB: Their spectra are complex, crowded, and non-standard!

Key: Local or Global Enrichment?

Basically just <u>two</u> explanations of these excesses:

- This is only a surface effect, produced locally; *or*
- The parent ISM cloud had this composition

<u>*Local production site(s):*</u>

- Production, diffusion or mixing <u>within</u> the star itself, or
- Transfer of processed matter from a binary companion

<u>*External production sites:*</u>

- Pollution of the parent cloud from a distant production site

Clue: <u>*Frequency and orbits*</u> of binaries in sample!

What Was Thought Before 2006?

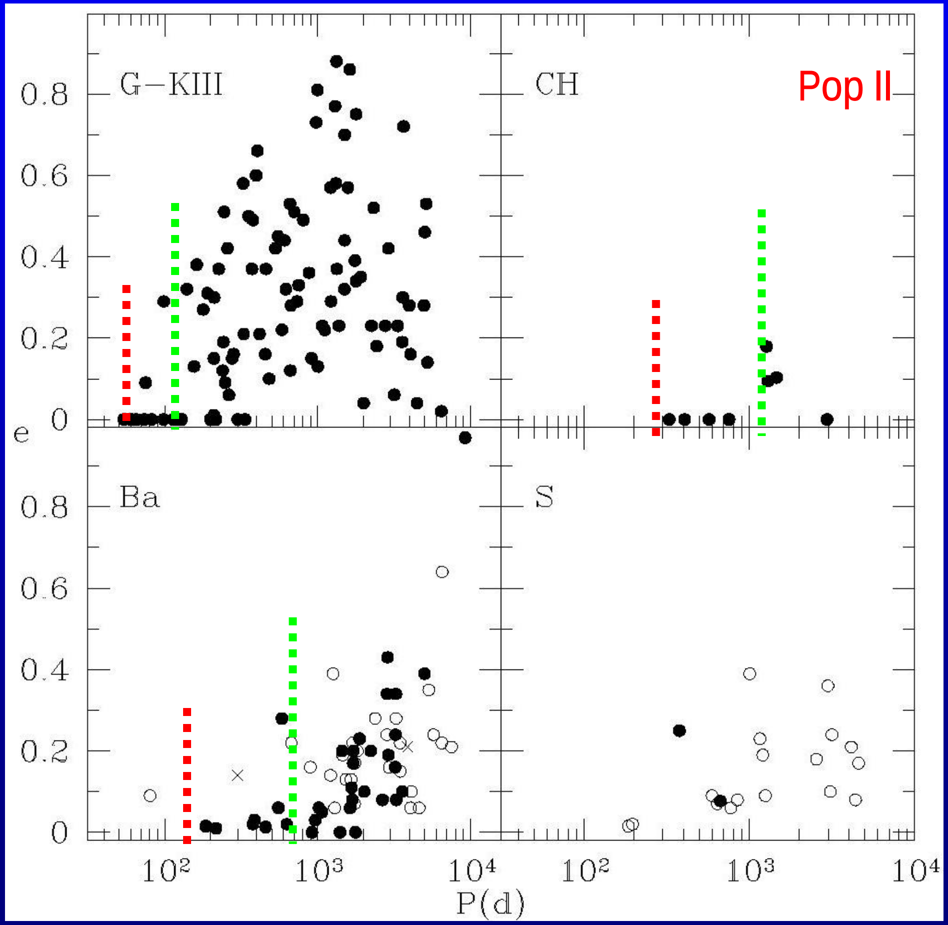
Conventional wisdom:
All chemical peculiarities were ascribed to binary evolution

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 Likely Transferred From a Former AGB Binary Companion



(Jorissen et al. 1998)

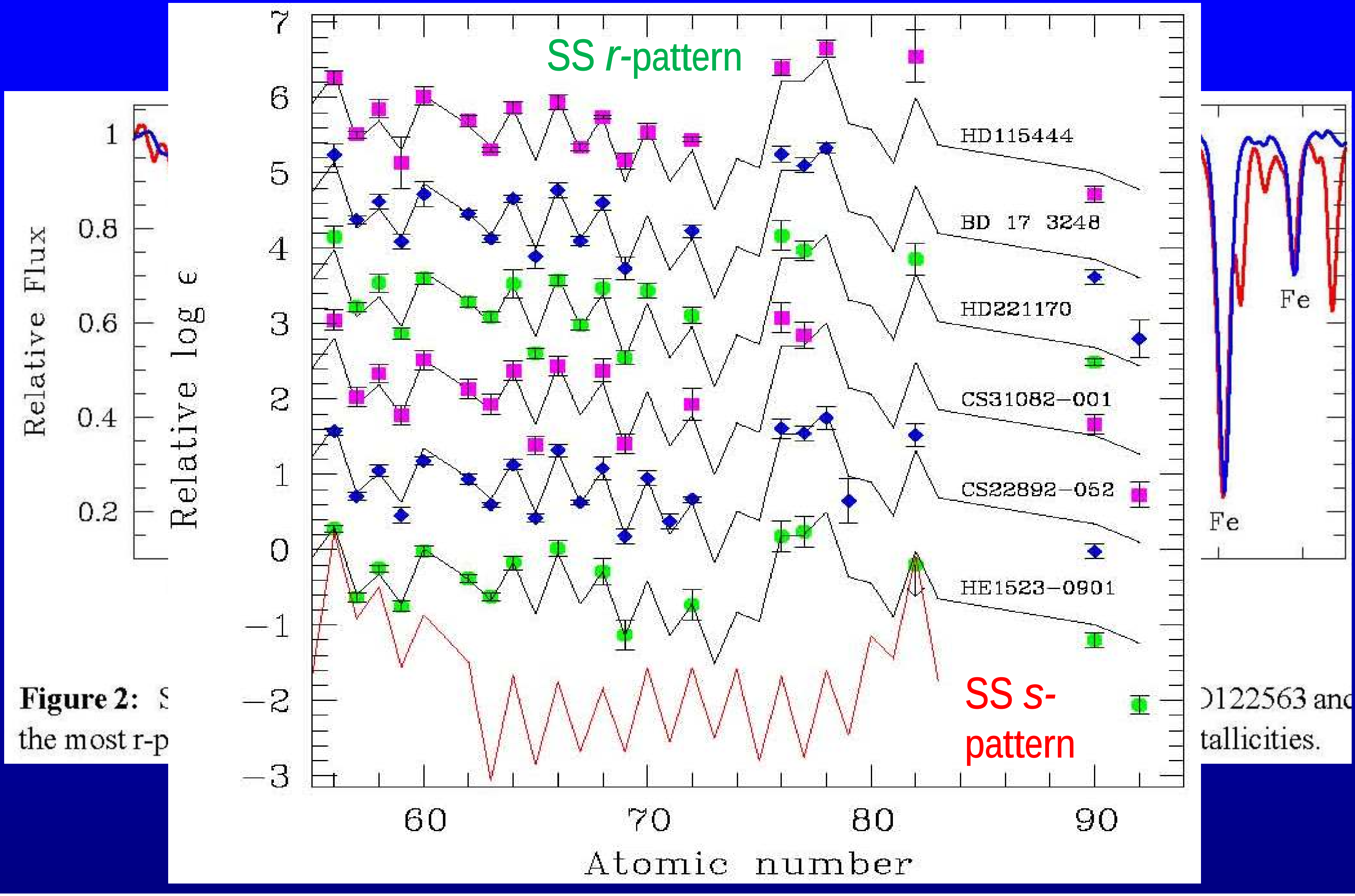
Note cutoff periods for:

common-envelope evolution (secondary R)

circularisation of orbits (Pop I: Depends on age)

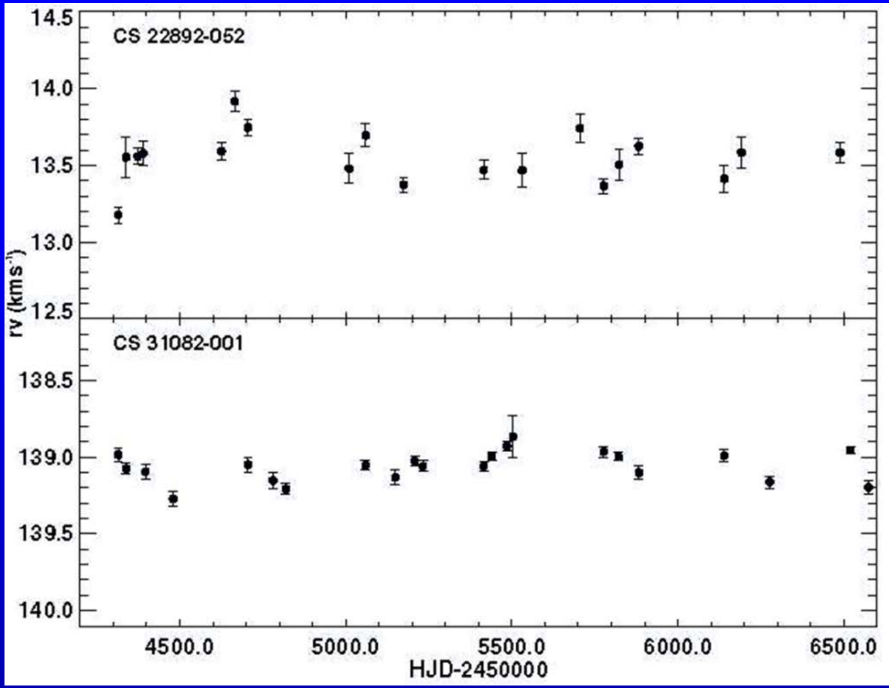
Theoreticians happy ☺

Do EMP-*r* (*r*-II) Stars Have a Similar Origin?



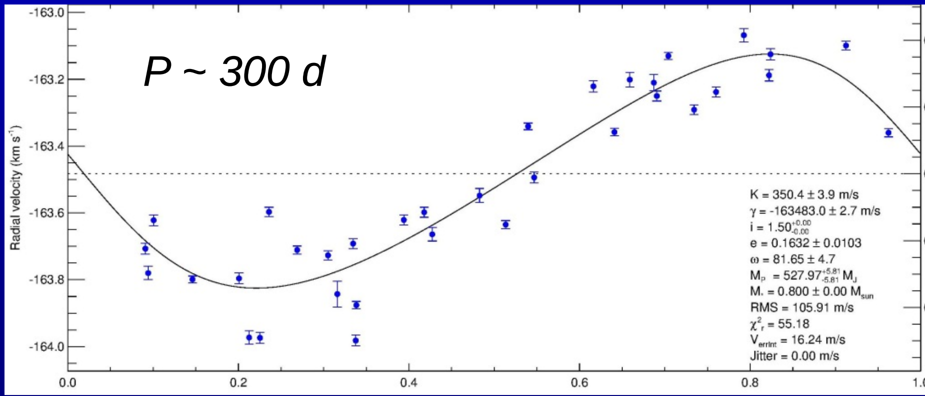
[Fe/H] = –3.0±0.2; *r*-element pattern very uniform, but offset by ≤ ~2 dex

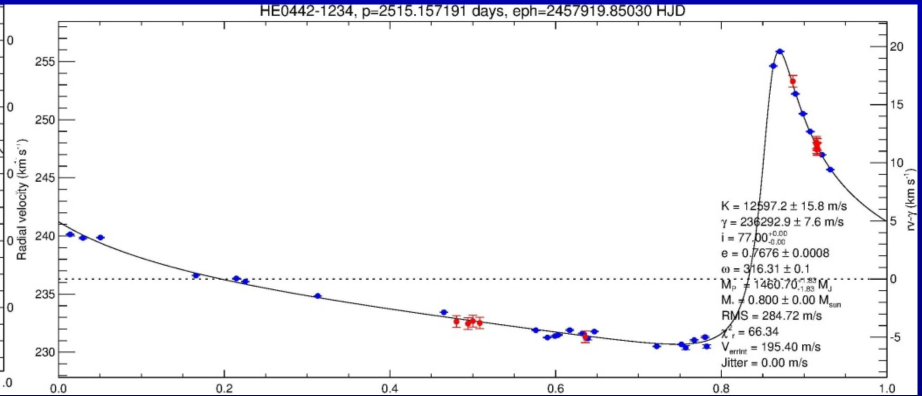
RV Monitoring With FIES@NOT (I)



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





CEMP Stars Were Now Important:

CEMP Stars Come in Two Varieties:

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:

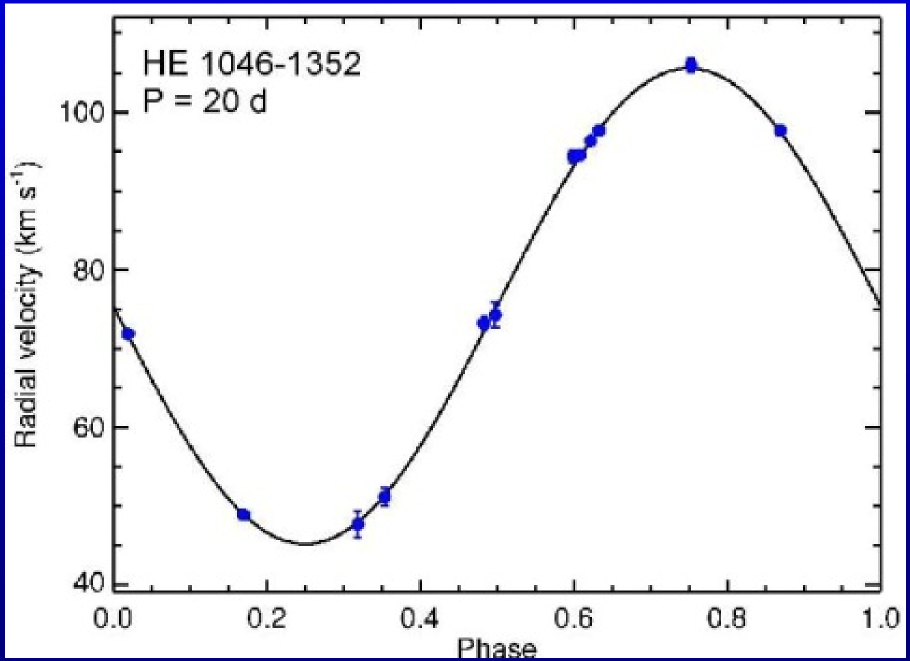
- Strong *s*-element signatures
- Dominate in inner halo
- Binary frequency high (simulations said 100%??)

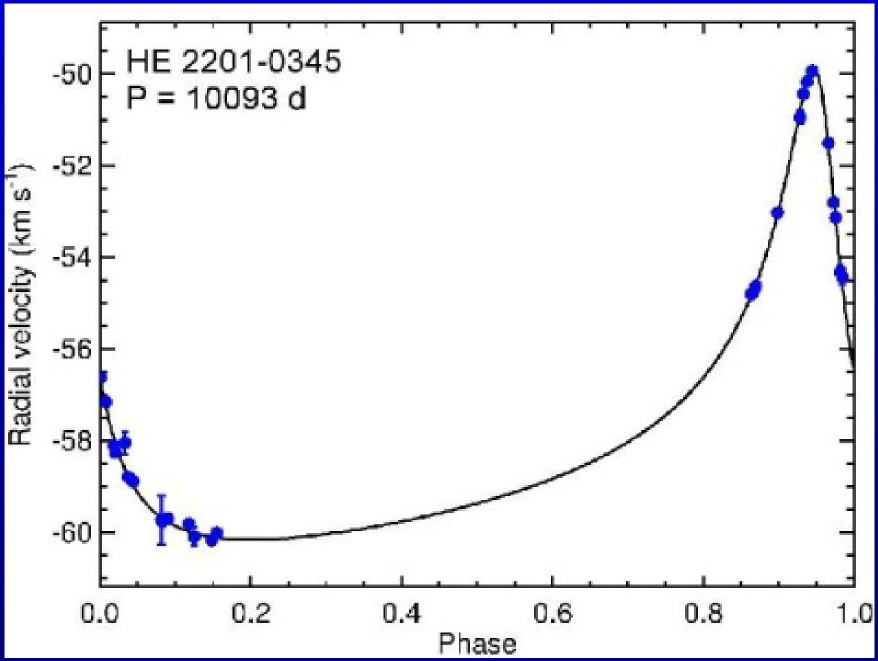
RV Monitoring With FIES@NOT (II)

Most (≥80%) CEMP-*s* stars are indeed binaries, but CEMP-no and EMP-*r* stars are generally *single*, and *some* (~20%) CEMP-*s* stars are single as well ($\sigma < 100$ m s^{-1}).

P = 20 d (post *common envelope*?)

P ~30 yr(!)



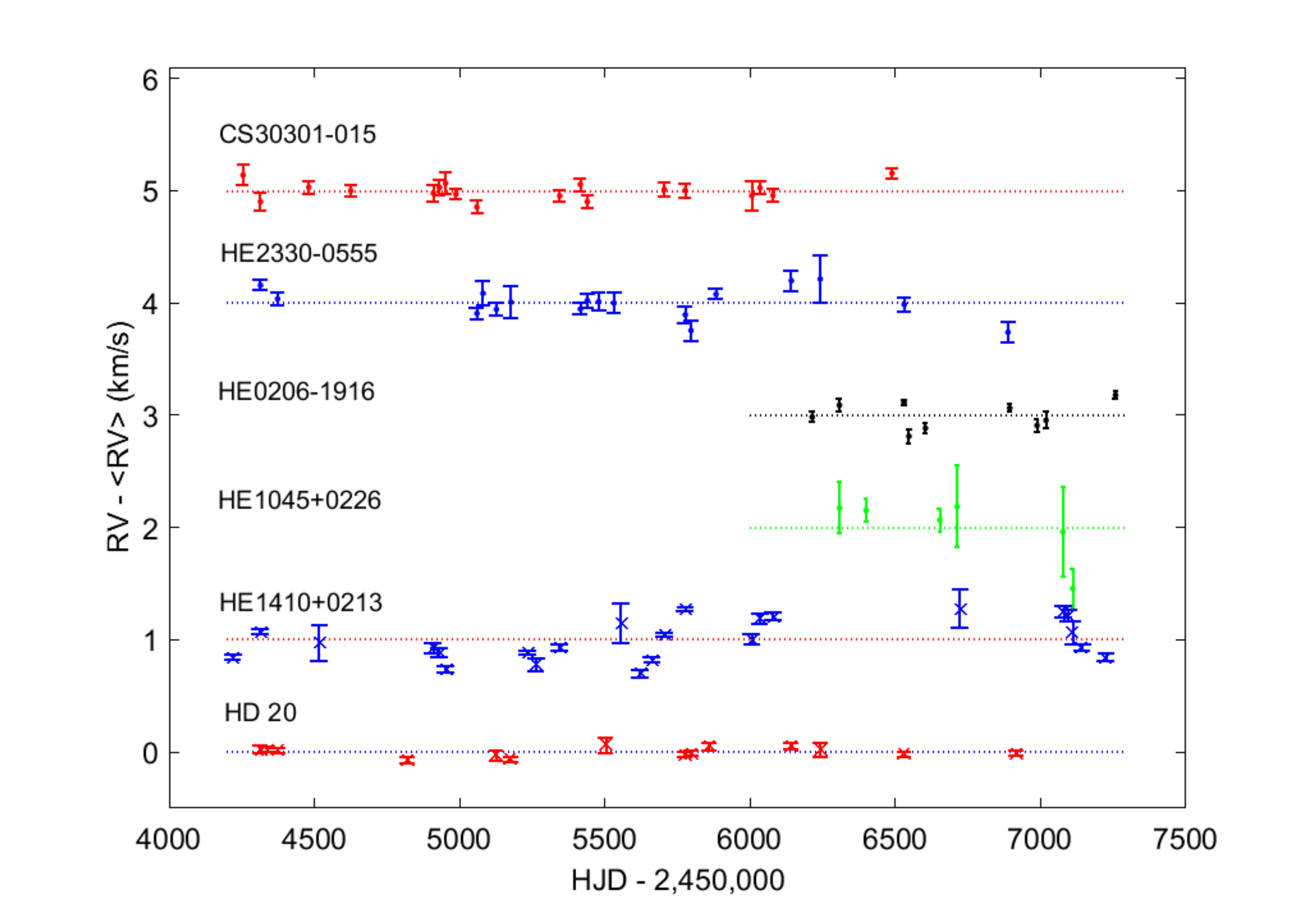


Follow-up I (2017+): Gaia π, d, L

- Distances
- Kinematics
- Evolution

\- are unknown!

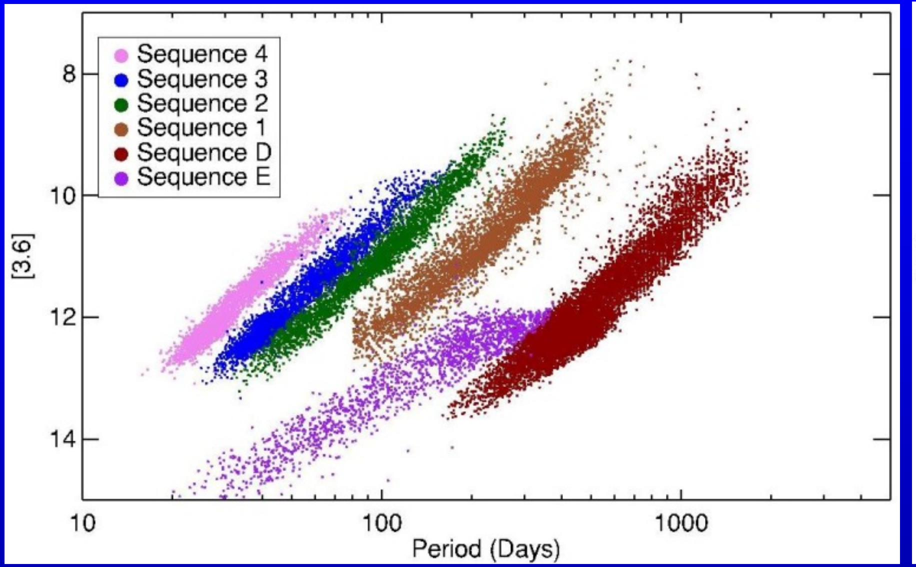
Are the stars Giants or AGB?

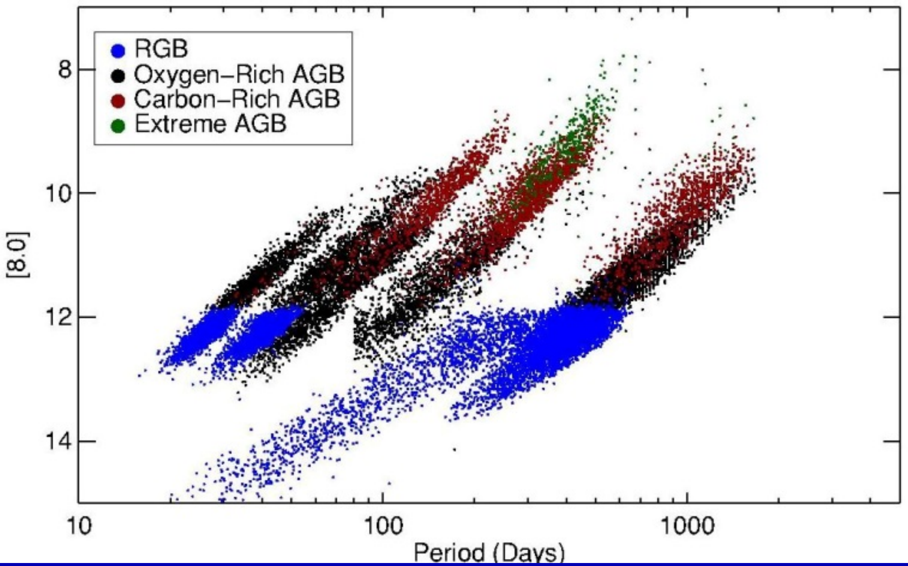


Some CEMP-s stars are variable

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

Tantalizing Results From the LMC:





Pulsating LMC RGB & AGB stars from MACHO and *Spitzer* (Riebel+ 2010). Sharp limit between RGB and AGB stars?
Gaia parallaxes will help to put our field stars on the same M_V scale.

Results/Conclusions:

- CEMP-no and EMP-*r* stars are basically ***single***
- ~20% of the CEMP-*s* stars are single as well(!)
- 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 $z \geq 3$(?)
- Some early enrichment processes were complex and *non-local*
- Could this process account for the C-rich DLAs at z = 2-3?
- Could the C in CEMP-no and the single CEMP-*s* stars originate in AGB stars without *s*-element production?
- Alternatives: 'Faint' SNe with fallback & mixing? Or 'spinstars'?
- Some CEMP stars seem to be *pulsating*; *Gaia* should tell if & why!

THANK YOU !

☺