Extremely Iron-Poor Stars and the Early Galaxy in the Context of Gaia

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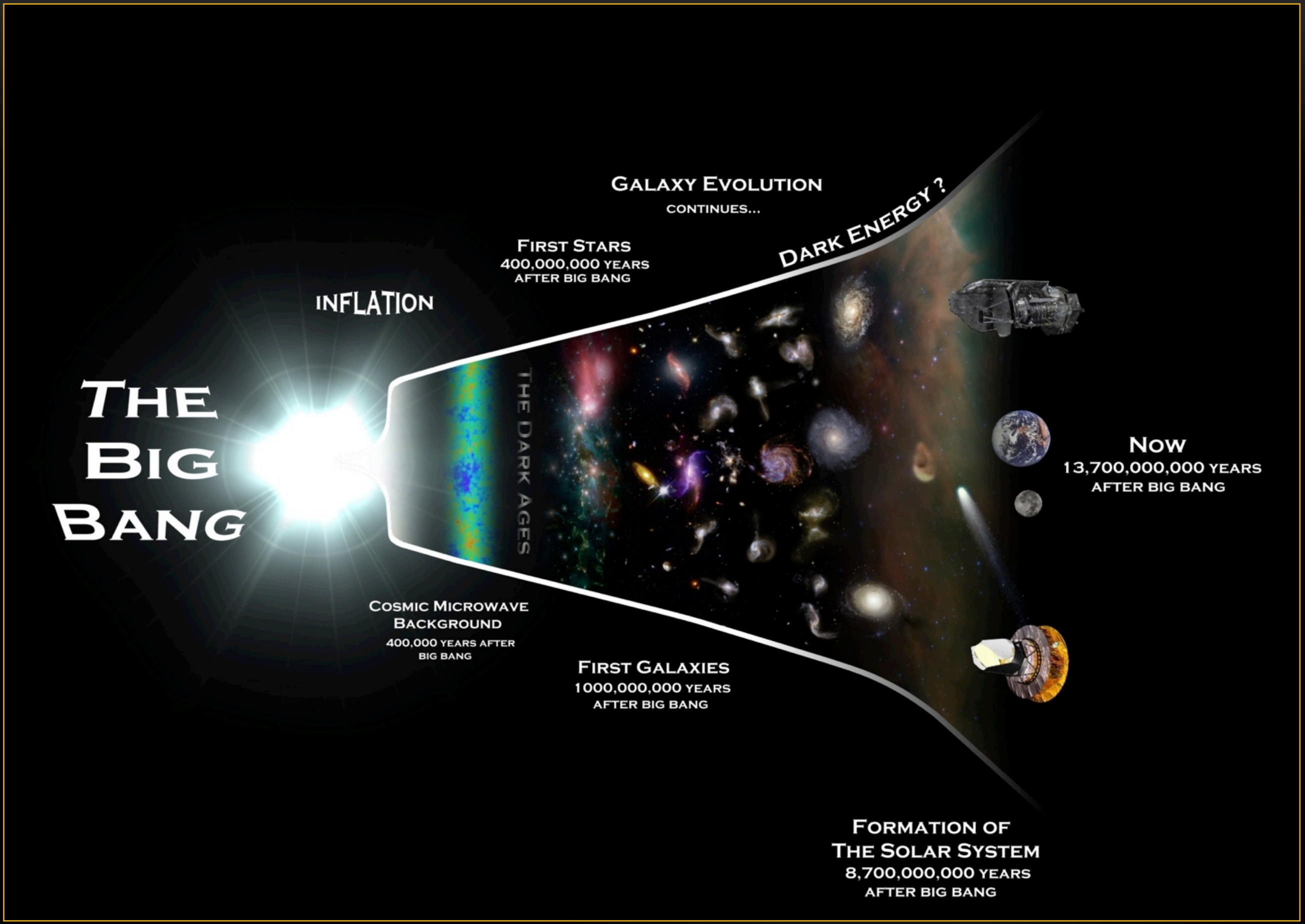
Expanding the Gaia legacy: the role of Spanish ground-based facilities

Aula Magna Enric Casasses, Facultat de Físiques UB

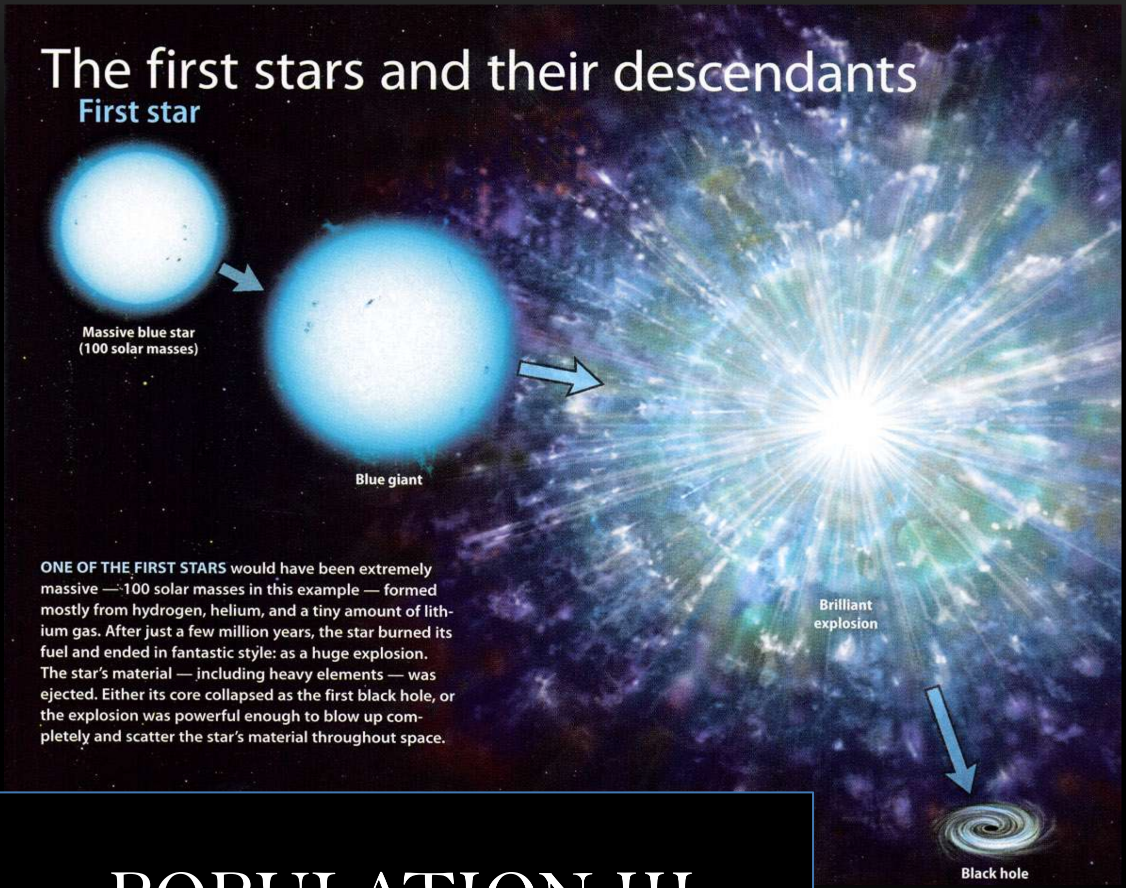
Barcelona, 19th February 2020

Formation of First Stars

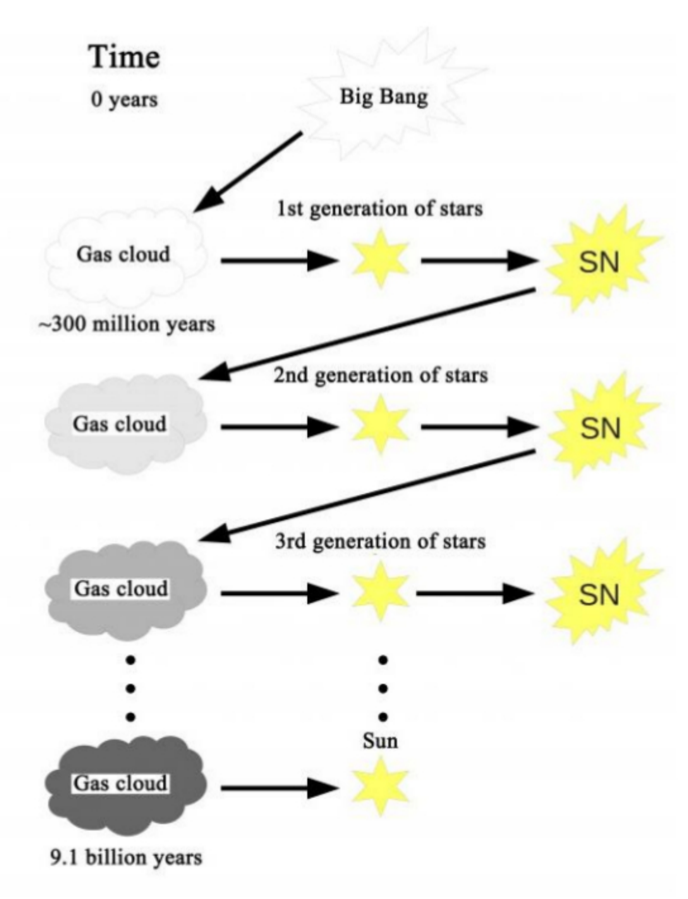


- SBBN : mostly H, ^{4}He, little D, ^{3}He and (very little 7Li)
- Metal-poor stars: Formation and evolution in the Early Universe
- EMP ([Fe/H] < -3) low-mass stars form with the gas polluted by the ejecta of PopIII massive stars
  -> constrain the conditions of the first 500 Myr of the Universe

Formation of First Stars



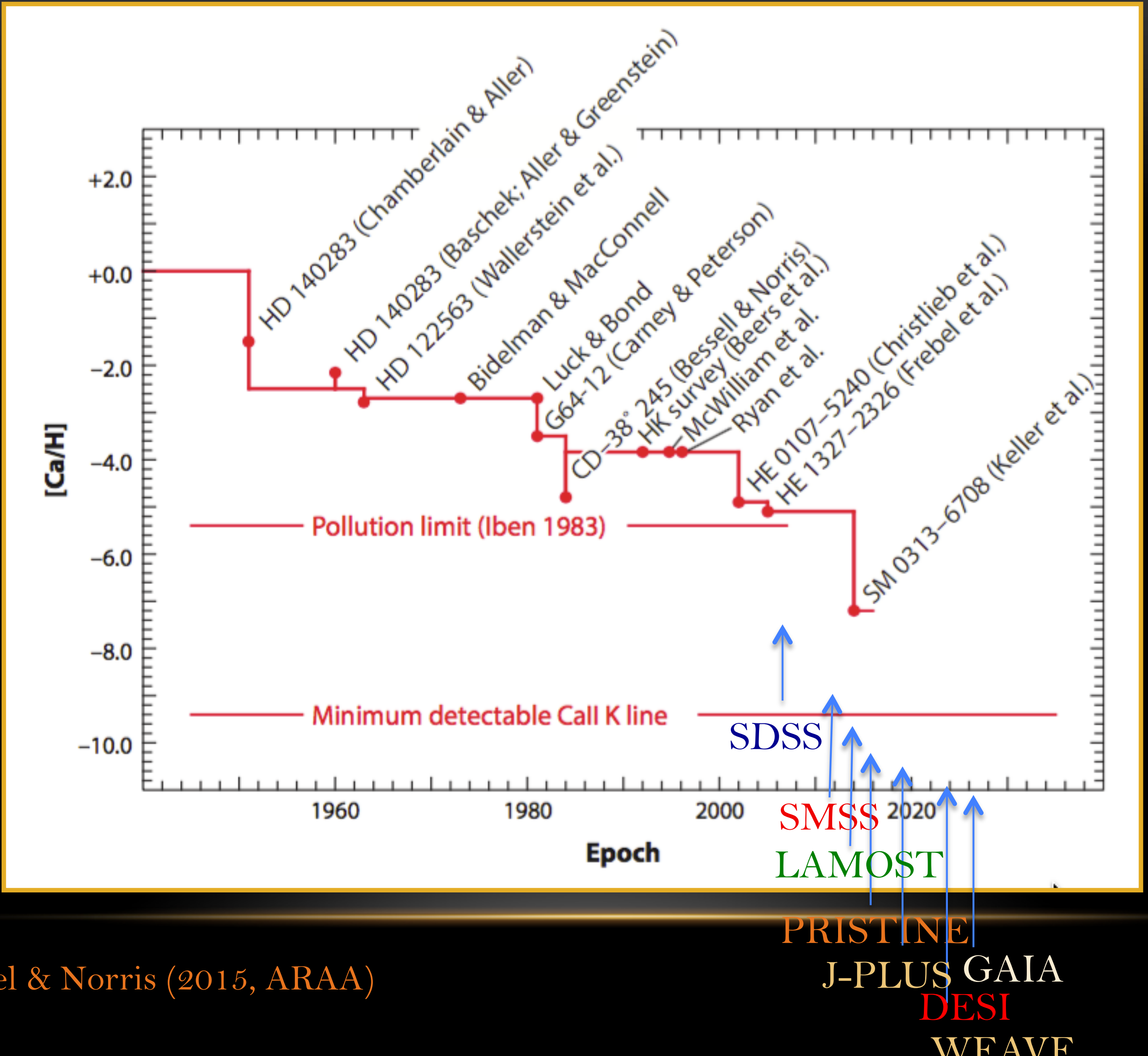
POPULATION III



https://www.4most.eu/cms/surveys/galactic/

- Clearly, identifying iron poor stars and measuring their chemical patterns in detail would provide information on the IMF and properties of Pop-III

History of Iron Poor Stars



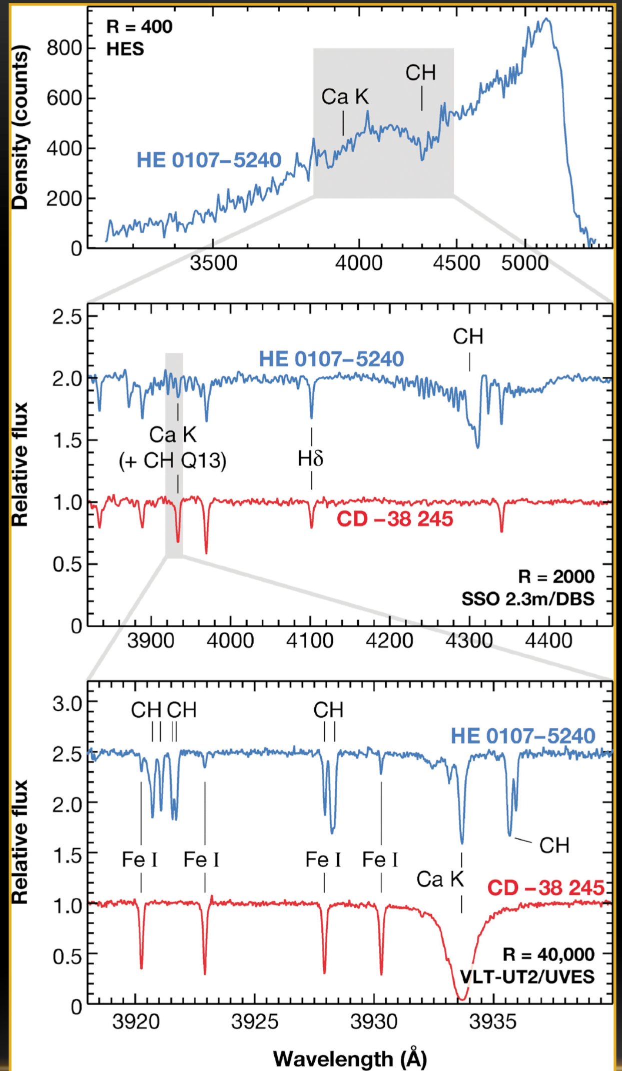
Frebel & Norris (2015, ARAA)

How to Find an (Old) EMP Star

Survey
large areas of the sky

Medium Res Spectra
for spectral vetting

High Res Spectra
Detailed spectroscopic analysis



Beers, TC and Christlieb, N. 2005
Annu. Rev. Astron. Astrophys. 43: 531–80

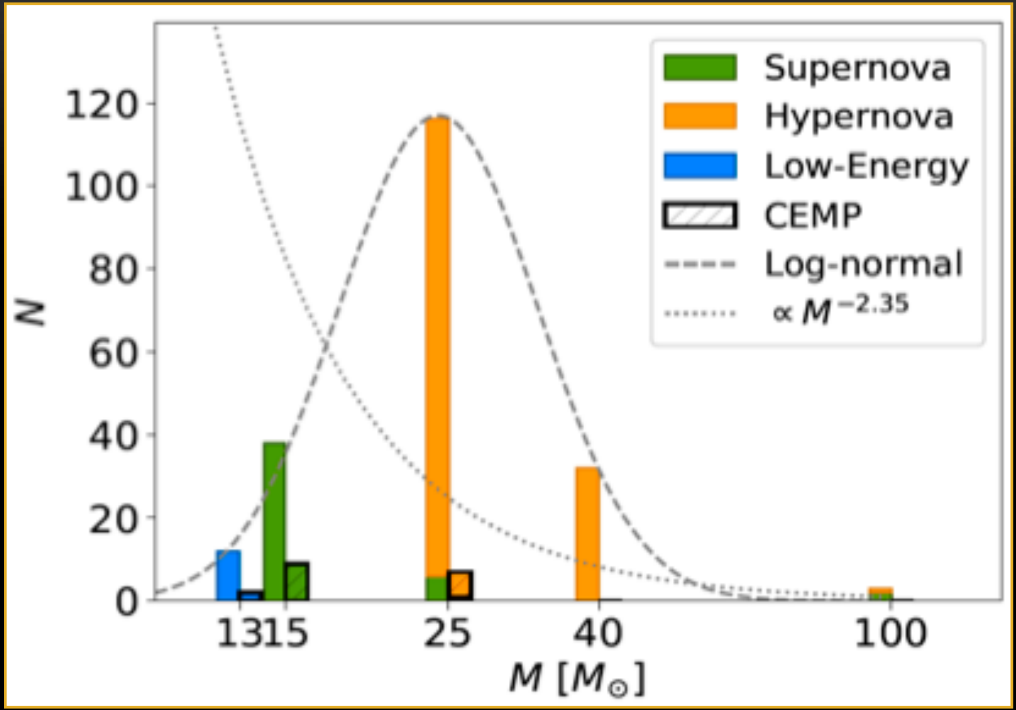
In a typical halo field
(V = 13 - 18)

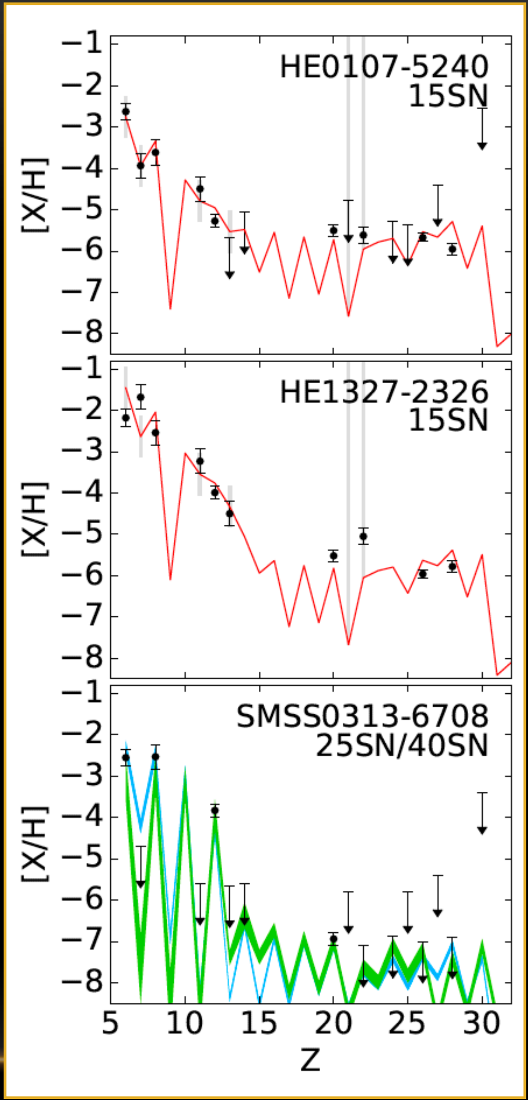
- 1 / 800 stars has [Fe/H] < -3
- Only 1 / 80,000 has [Fe/H] < -4
- But only ~14 known with [Fe/H] < -4.5

RAVE
460,000 stars
LAMOST
5.3 million stars
APOGEE
450,000 stars
SDSS (SEGUE+BOSS)
960,000 stars
Gaia-ESO:
100,000 stars

Beers & Christlieb 2005

IMF and SN/HN - First Stars





Abundance Profiling ~200 stars with [Fe/H] < -3
Ishigaki et al. (2018); Tominaga et al. (2014)

- Element abundances from C to Zn were compared with supernova
- yields of metal-free stars with masses of 13, 15, 25, 40, & 100 M◉,
- and variety of mixing and fallback parameters.

- **Nearly all EMP stars can be fit with yields from SN/HN with ~"normal" masses.**

Most Iron-Poor Stars [Fe/H] < -4.5

Starname	[Fe/H]	[C/Fe]	References
HE 0233-0343	-4.68	+3.32	Hansen et al. (2014)
HE 0557-4840	-4.75	+1.66	Norris et al. (2007, 2012); Masseron et al. (2012)
SDSS J1742+2531	-4.80	+3.63	Caffau et al. (2013); Bonifacio et al. (2015)
SDSS J1029+1729	-4.99	<+0.70	Caffau et al. (2011, 2012)
SDSS J1313-0019	-5.00	+2.96	Allende Prieto et al. (2015); Frebel et al. (2015)
SDSS J1035+0641	<-5.20	>+3.87	Bonifacio et al. (2015, 2018)
HE 0107-5240	-5.54	+2.69	Christlieb et al. (2002, 2004)
HE 1327-2326	-5.65	+3.48	Frebel et al. (2005, 2008); Aoki et al. (2006)
SMSS J0313-6708	<-7.30	>+5.39	Keller et al. (2014); Bessel et al. (2015)
SDSS J0929+0238	-4.99	+3.91	Caffau et al. (2016)

10 stars at [Fe/H] < - 4.5 (known in 2016)

2 < logg < 3
3 < logg < 4
logg > 4

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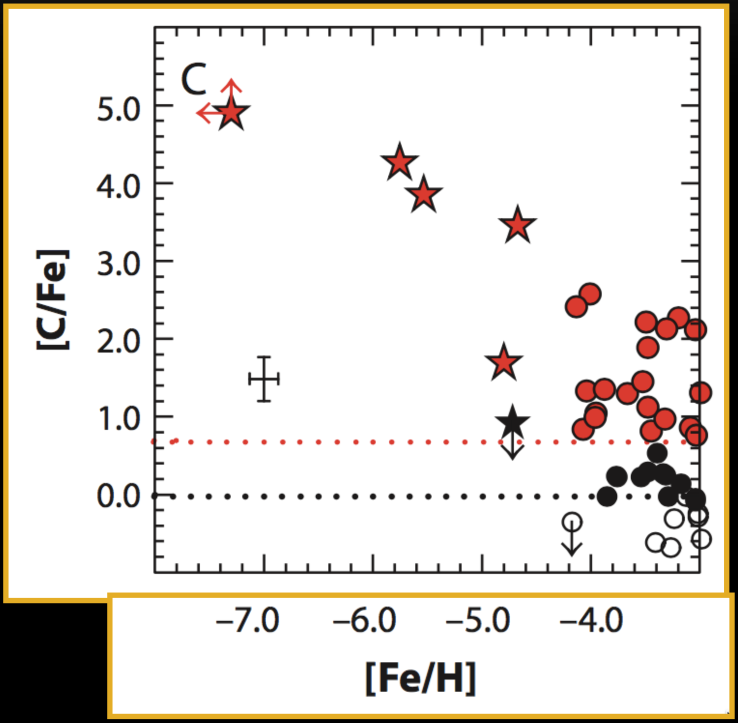
SDSS J0815+4729	-5.50	+4.60	Aguado et al. (2018a); González Hernández et al. (2020)
SDSS J0023+0307	<-6.10	>+3.91	Aguado et al. (2018b, 2019)
PR 221.878+9.78	-4.66	<+1.76	Starkenburg et al. (2018)
SMSS J1605-1443	-6.20	+3.89	Nordlander et al. (2019)

2 < logg < 3
3 < logg < 4
logg > 4

14 stars at [Fe/H] < - 4.5 (known in 2019)

C-Enhanced Iron Poor Stars



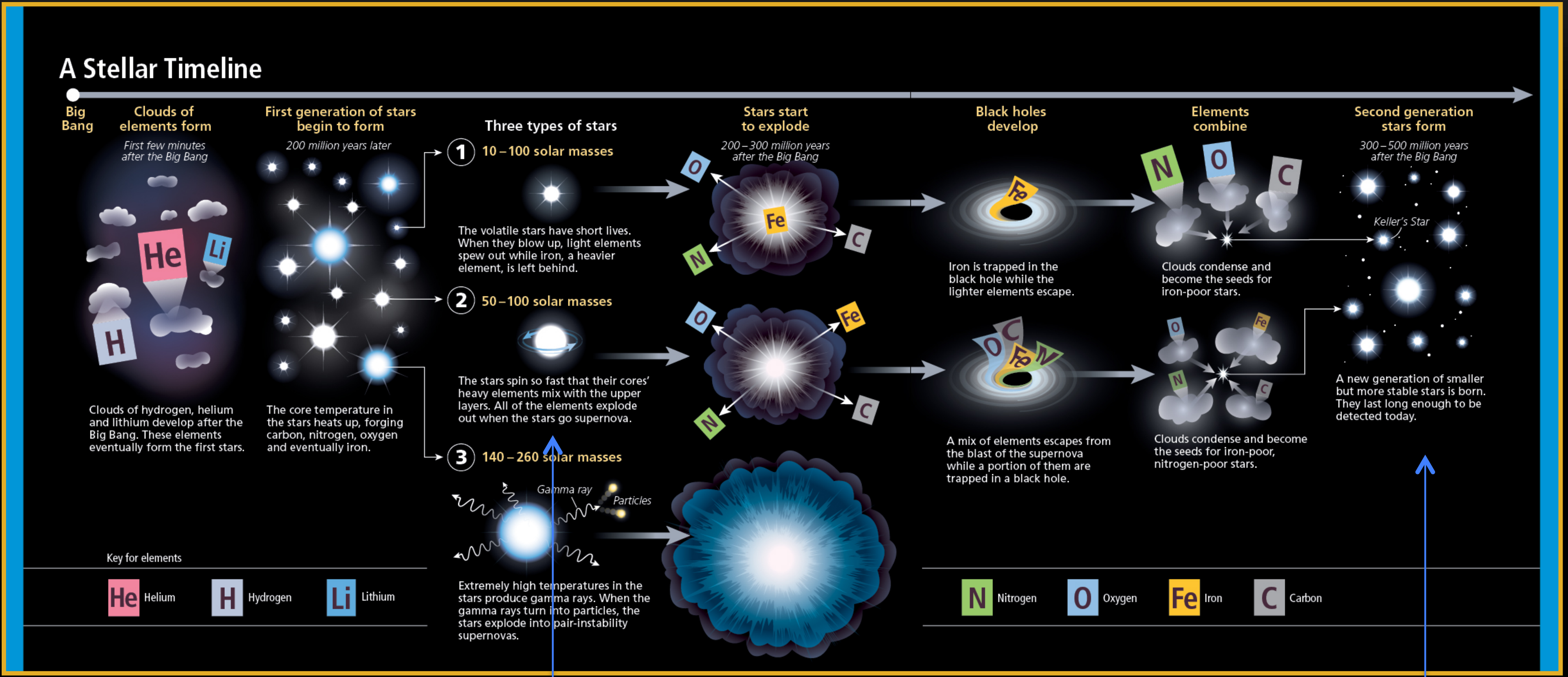
# of C-enhanced stars increases towards lower metallicities: [C/Fe]>+0.7

- 20% for [Fe/H] < -2.0
- 43% for [Fe/H] < -3.0
- 81% for [Fe/H] < -4.0

- Is there a minimum metallicity to form low-mass stars ?

Frebel & Norris (2015, ARAA)

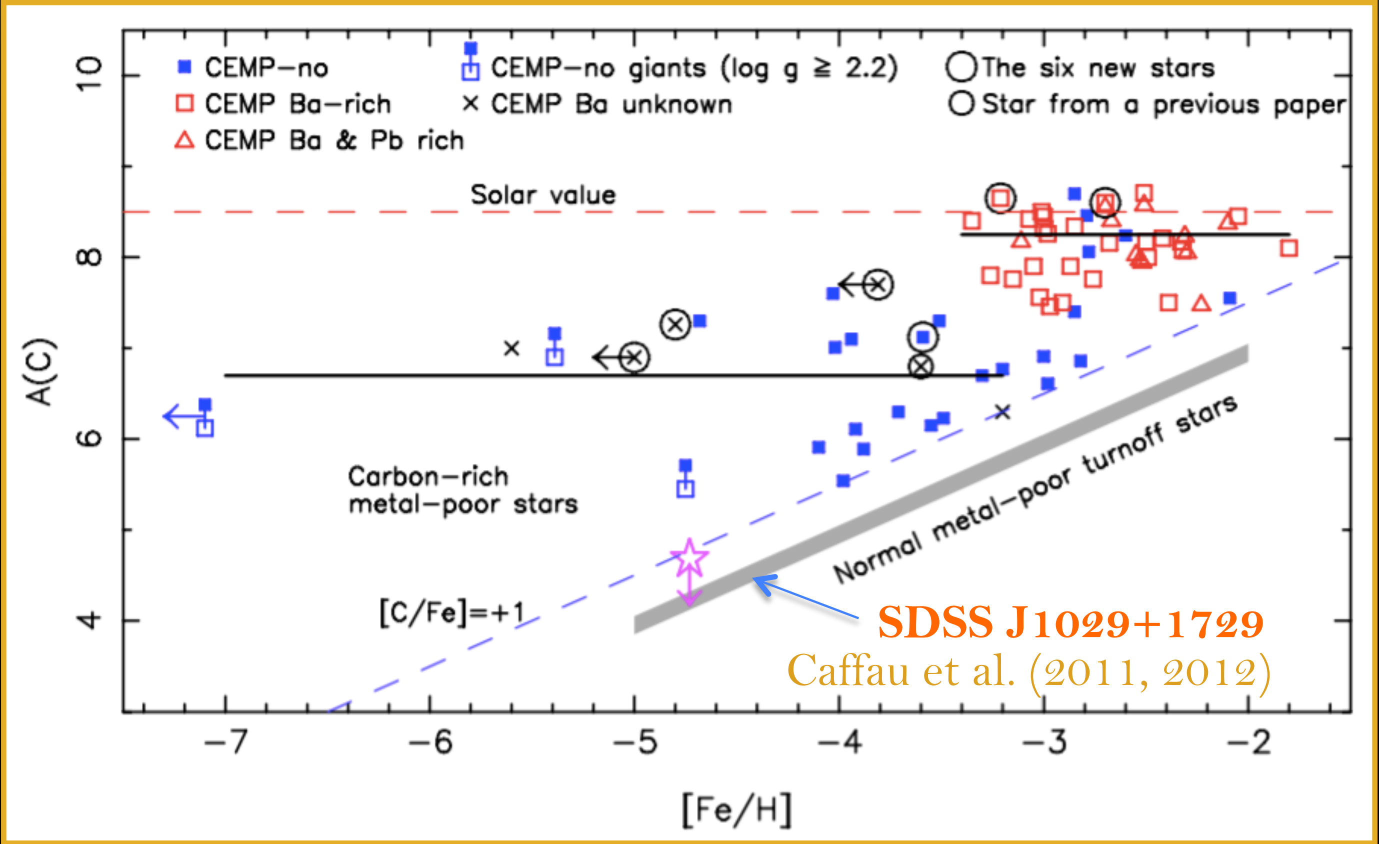
Formation of First Stars



Study these stars

To understand the First stars

C-Enhanced Metal Poor Stars

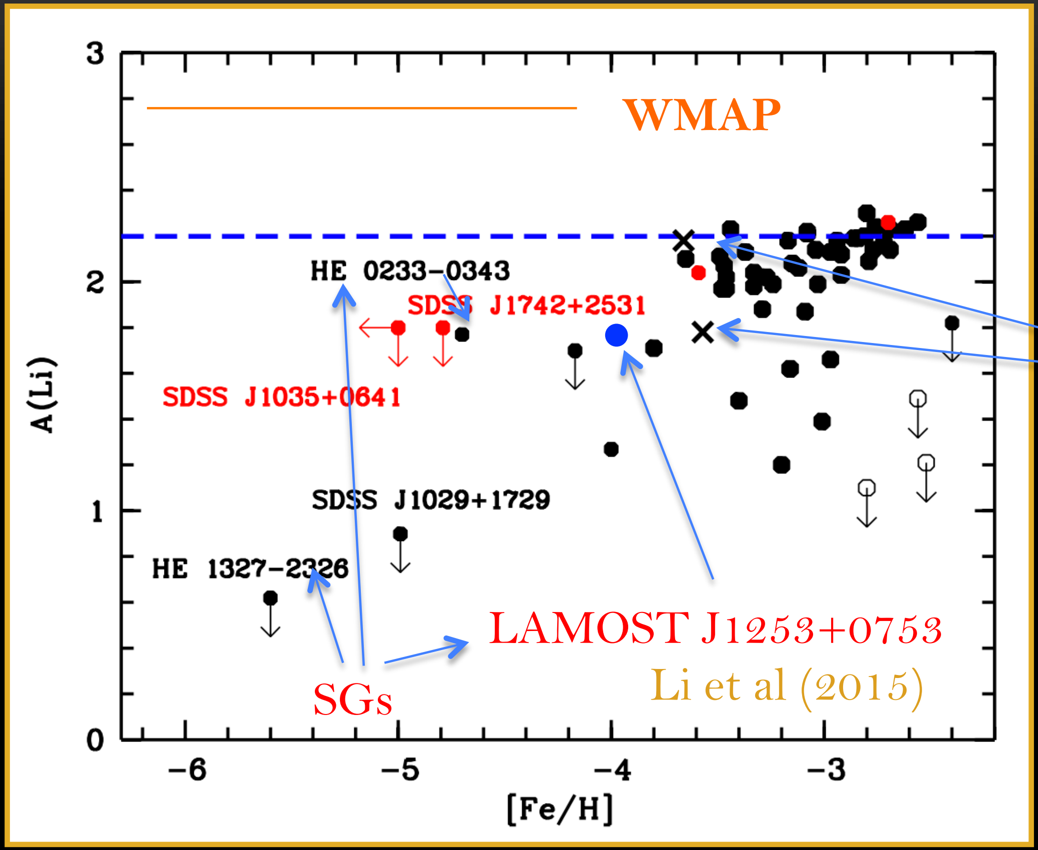


Only unevolved stars:
Logg > *2.2*

- Bimodal distribution of C abundances in EMPs
  - High-carbon stars -> Ba rich
  - Low-carbon stars -> CEMP-no

Bonifacio et al. (2015); Spite et al. (2013)

Lithium in Unevolved Extremely Metal Poor Stars



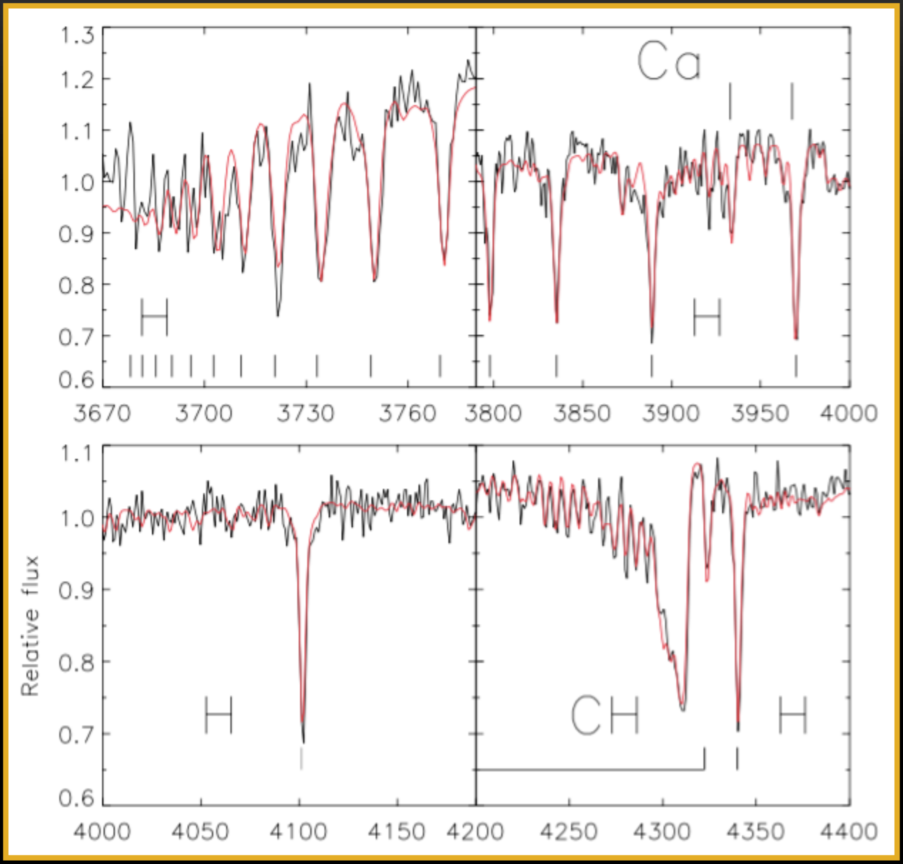
CS 22876 -032 AB

González Hernández et al. (2008, A&A)

The discrepancy with WMAP/Planck predicted Li from SBBN remains unresolved

Bonifacio et al. (2015, A&A)

SDSS: NEW UMPs



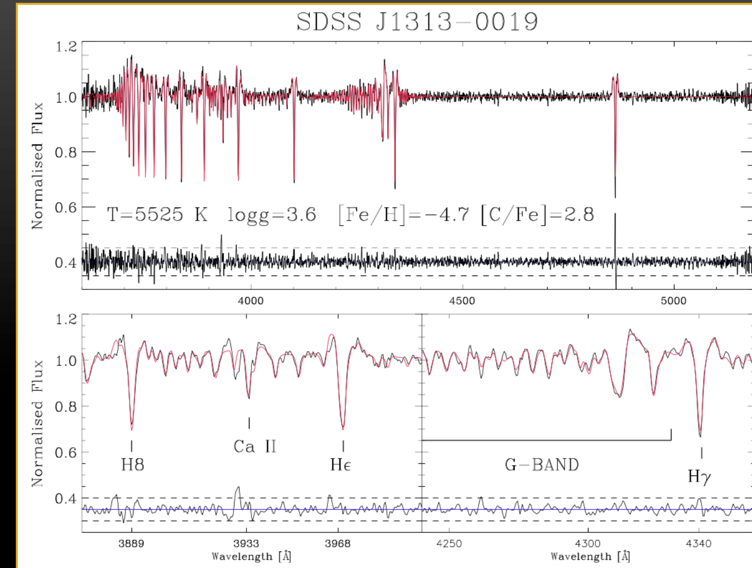
BOSS spectra (R~2000)
(Allende Prieto et al. 2015, A&A) :

SDSS spectrum of the star SDSS J1313-0019 (g = 16.9)
*T*eff = 5300K, logg = 2.50, [Fe/H] = - 4.3

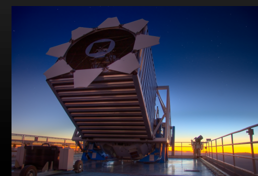
The analysis was done using the FERRE code (see e.g. Allende Prieto et al. 2014, A&A)

Result using high resolution spectroscopy
*T*eff = 5200+-150 K, logg = 2.6+-0.5
[Fe/H] = - 5.0+-0.1 (Frebel et al. 2015)

METHODOLOGY: NEW UMPs



- EMP and UMP candidates from
  - SDSS (R~2000)



  - LAMOST (R~1800)

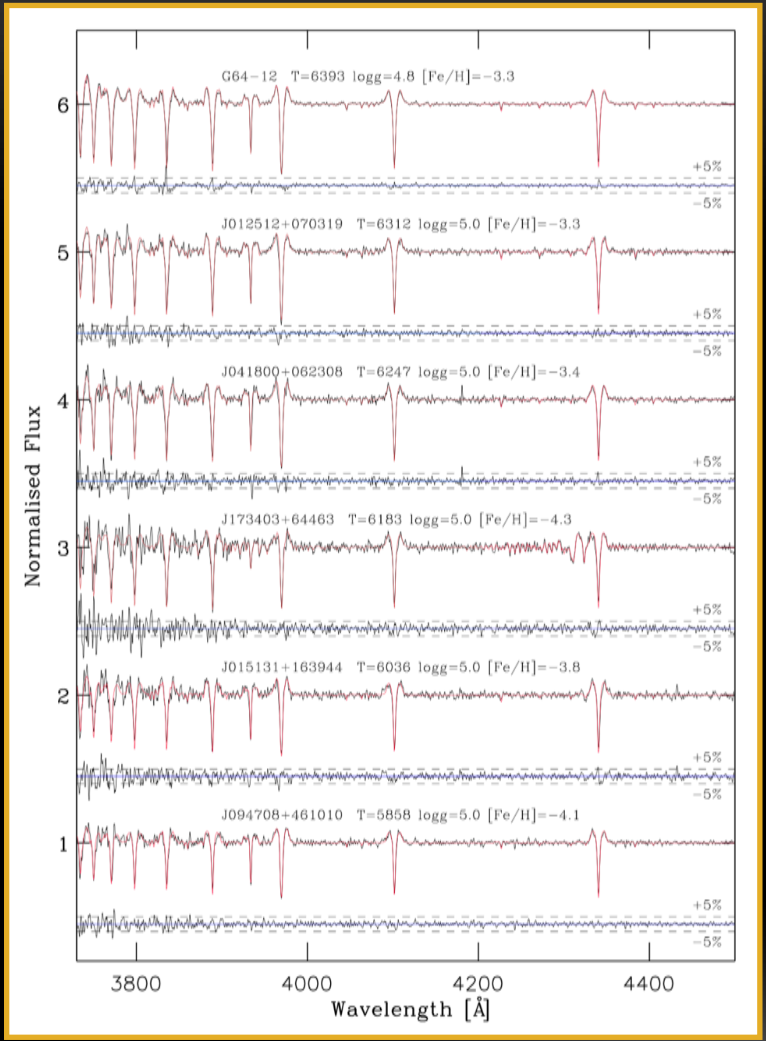
- ~2.5 million stellar spectra analysed with FERRE
- Follow-up spectroscopy

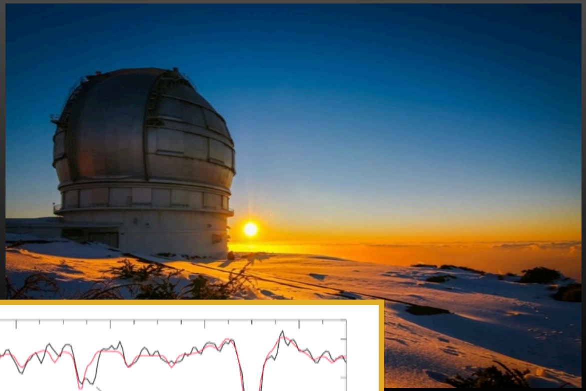
  - ISIS@4.2m-WHT (R~2400)
  - OSIRIS@10.4m-GTC (R~2500)
  - HRS@9.2m-HET (R~15,000)

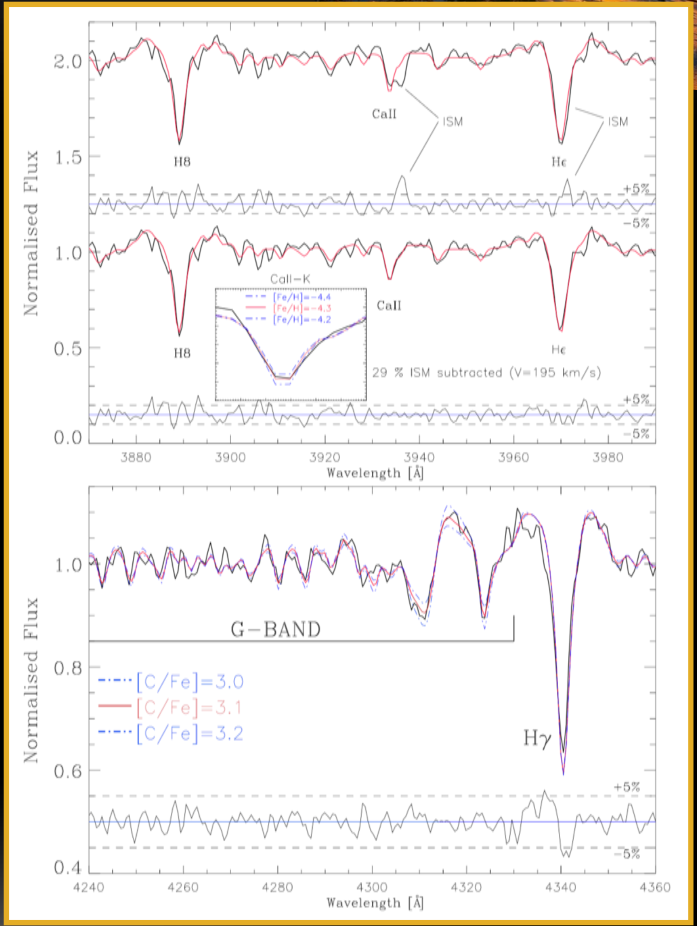
  - 4 UMPs y 29 EMPs

Aguado et al. (2016, A&A; 2017a, A&A; 2017b, A&A)

OSIRIS@GTC SPECTRA



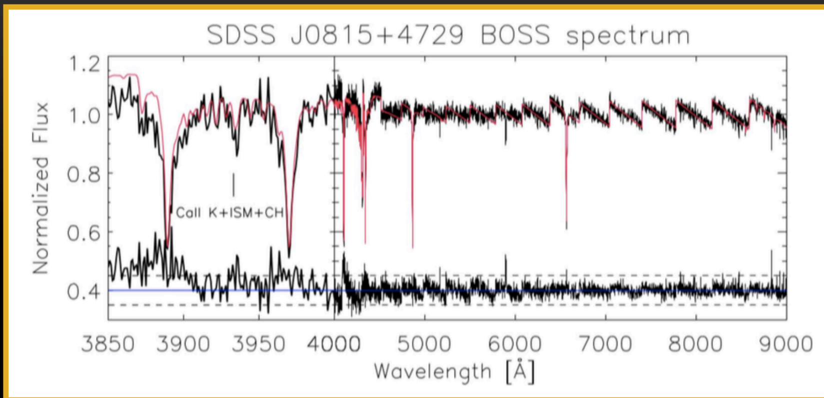


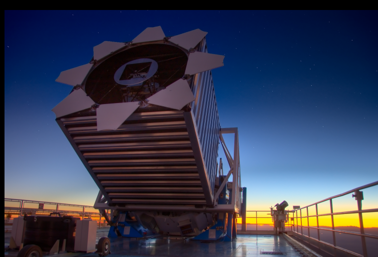


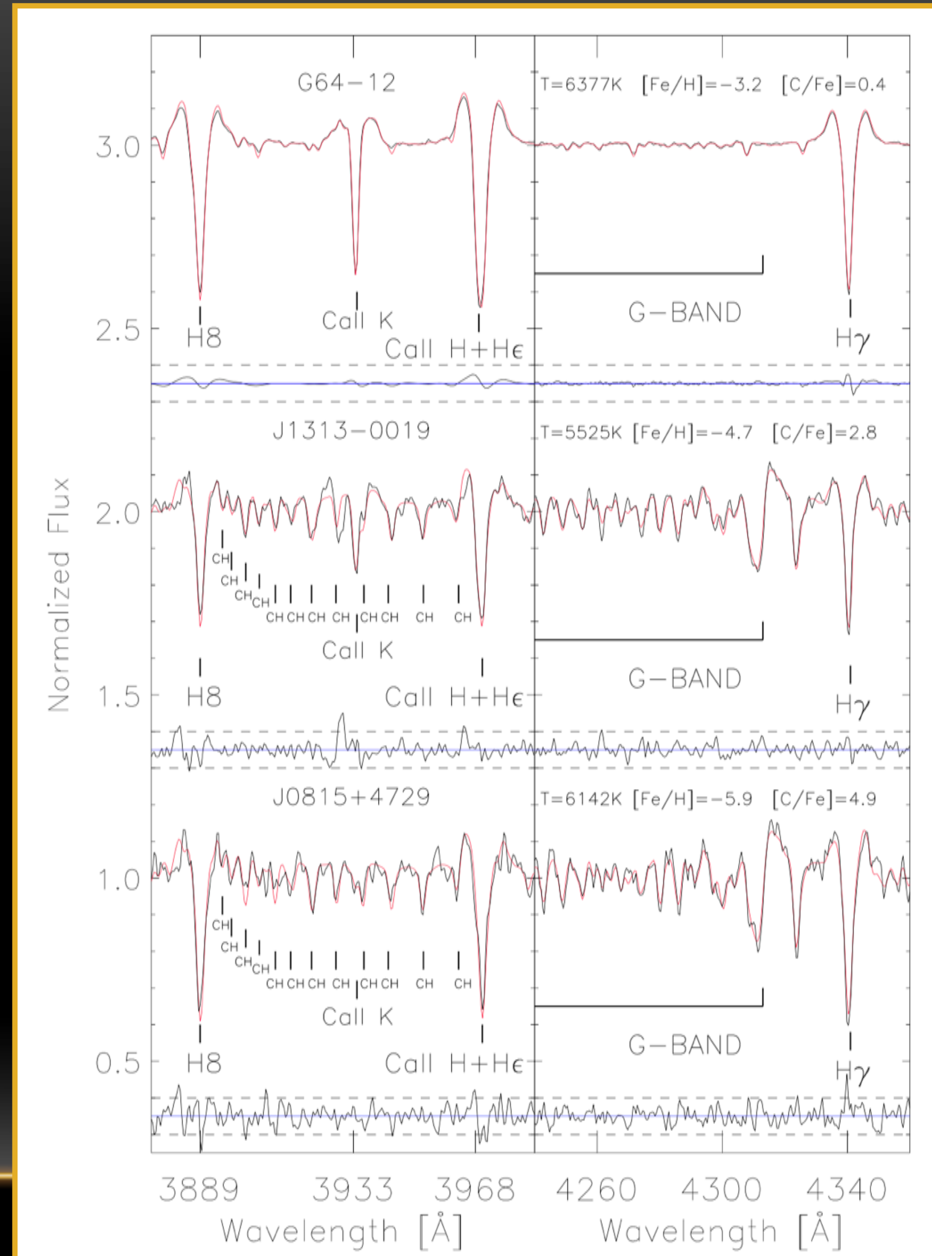
Aguado et al. (2017b, A&A)

J1734+6446: the faintest C-rich UMP known (g ~ 19.6) with GTC!!

J0815: BOSS + ISIS







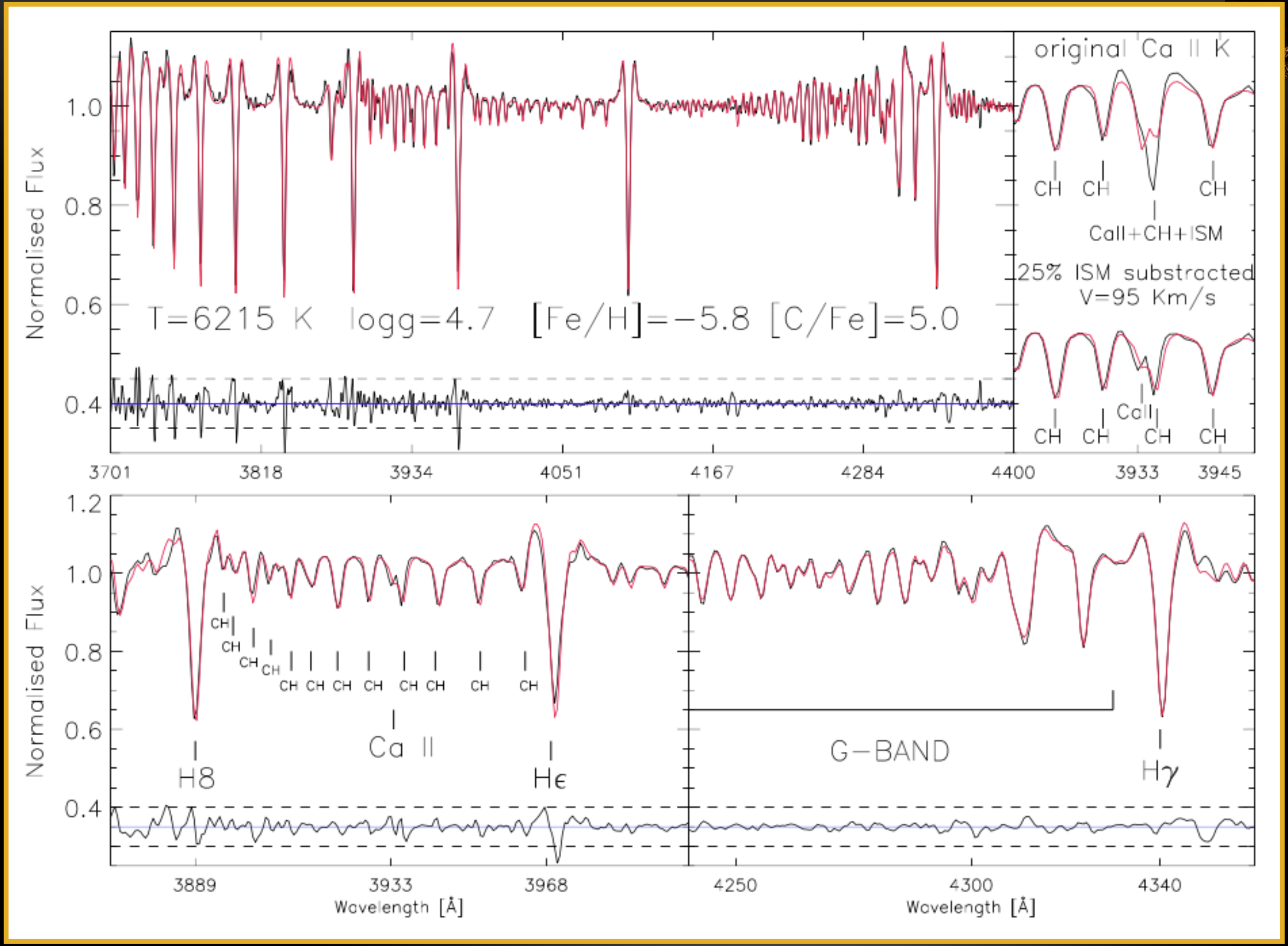
ISIS@WHT: 6 x 1800s

J0815+4729: a HMP dwarf star

(Fe/H] < -5.8)

Aguado et al. (2018a, ApJ Letters)

J0815: BOSS + ISIS + OSIRIS



Normal Progam
+DDT :
10 x 1600s

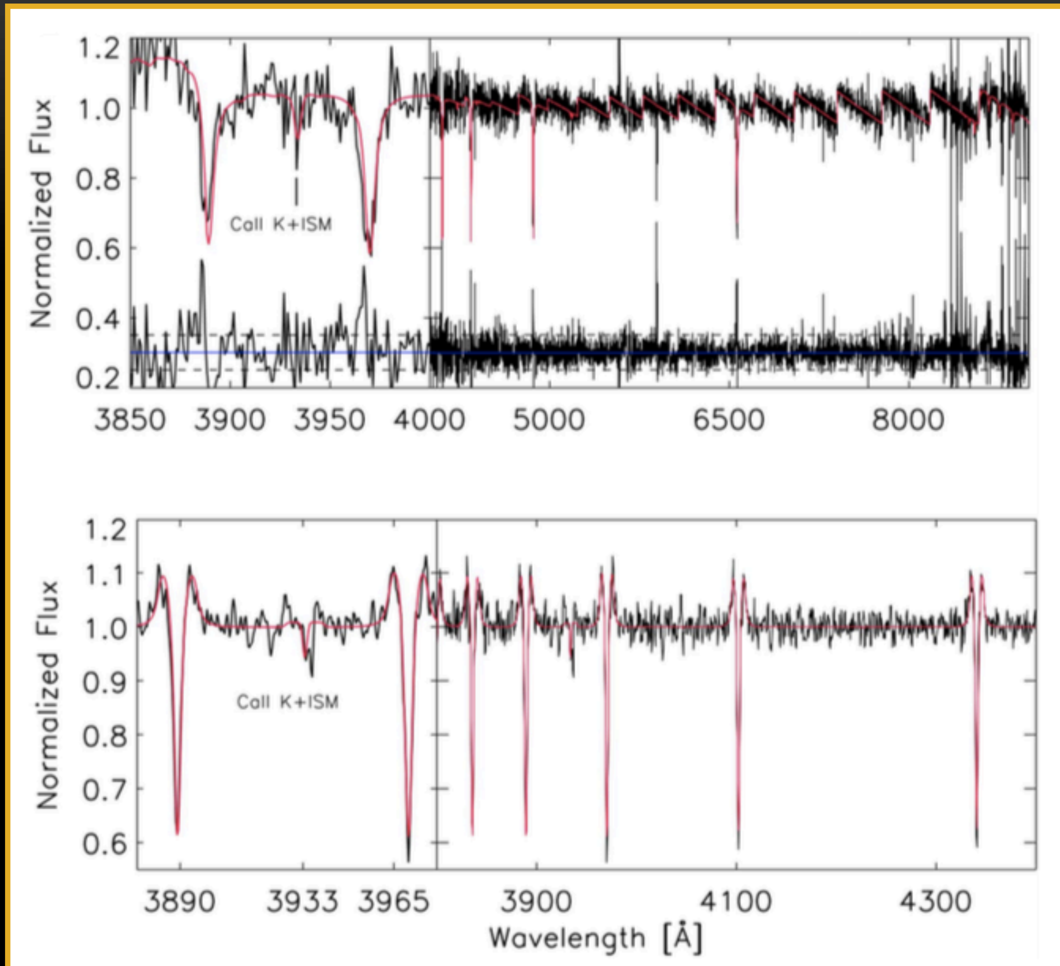
g ~ 17.05

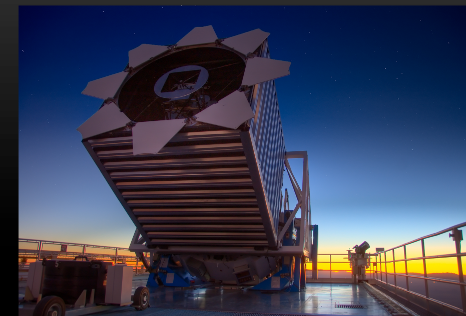
S/N ~ 200

J0815+4729: a HMP dwarf star (Fe/H] < -5.8) with the highest A(C) ~ 7.7

Aguado et al. (2018a, ApJ Letters)

J0023: BOSS + OSIRIS



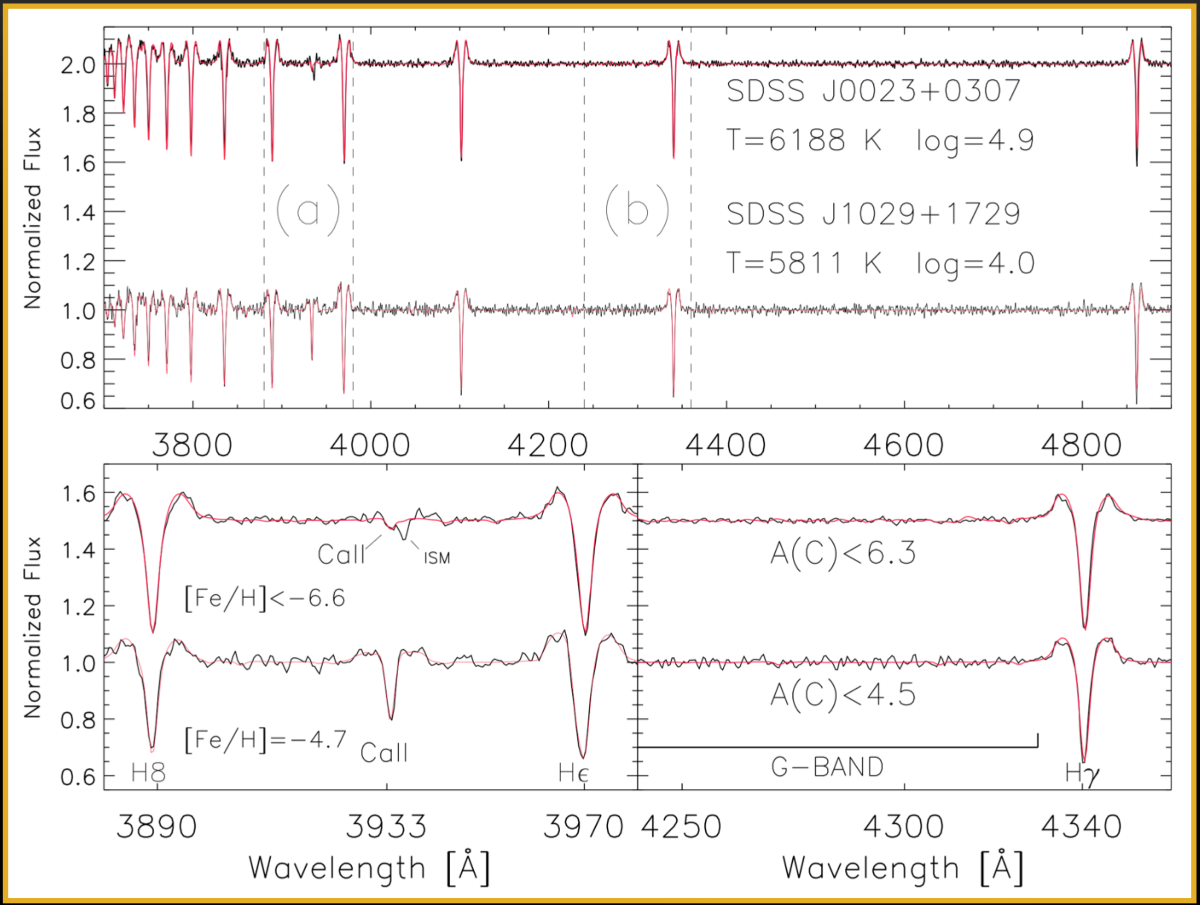


DDT-GTC: 10 x 1300s

J0023+0307: a MMP dwarf star (Fe/H] < -6.6) with the A(C) < 6.3

Aguado et al. (2018b, ApJ Letters)

J0023: BOSS + ISIS + OSIRIS



g ~ 17.9

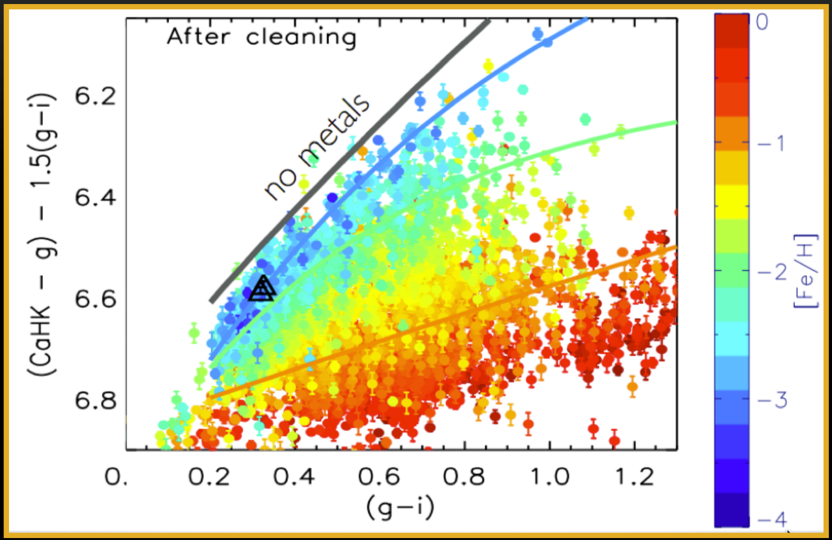
ISIS@WHT: 69 x 1800s

S/N ~ 170

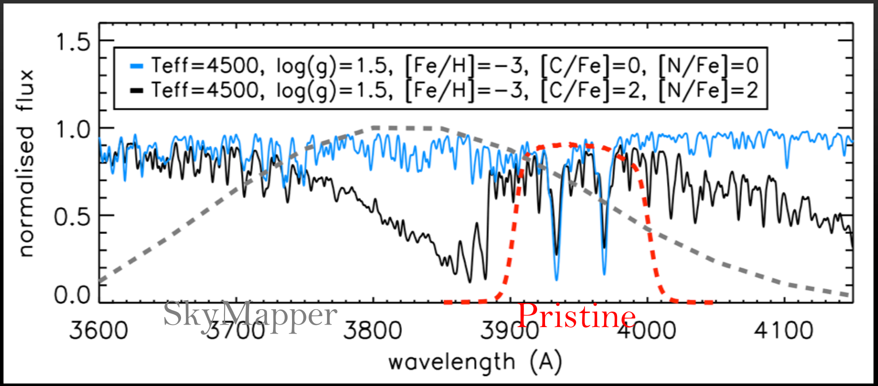
J0023+0307: a MMP dwarf star (Fe/H] < -6.6) with the A(C) < 6.3

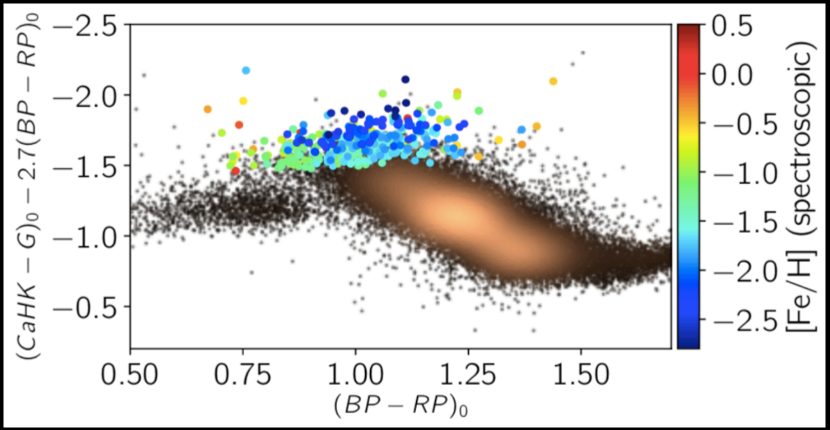
Aguado et al. (2018b, ApJ Letters)

Pristine Photometric Survey



Starkenburg et al. (2017, MNRAS)





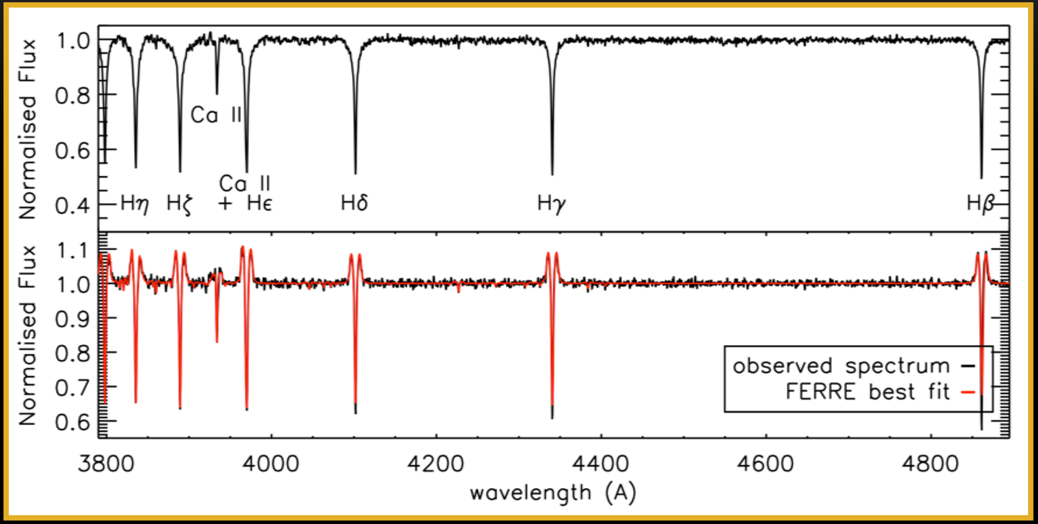
Arentsen et al. (2020, MNRAS Letters)

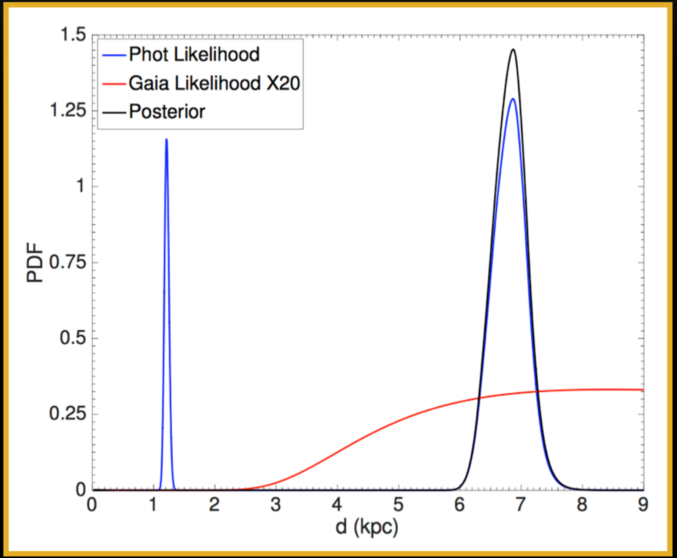
Follow-up spectroscopy using

- IDS@2.5m-INT (R~3300)
- ISIS@4.2m-WHT (R~2400)
- OSIRIS@10.4m-GTC (R~2500)
- CHFT, VLT, Keck…

Isis+ Uves: PR221

IDS@INT Spectra





- ISIS spectrum : Teff ~ 5871 +- 80 K
- IRFM (APASS + UKIDSS/2MASS):

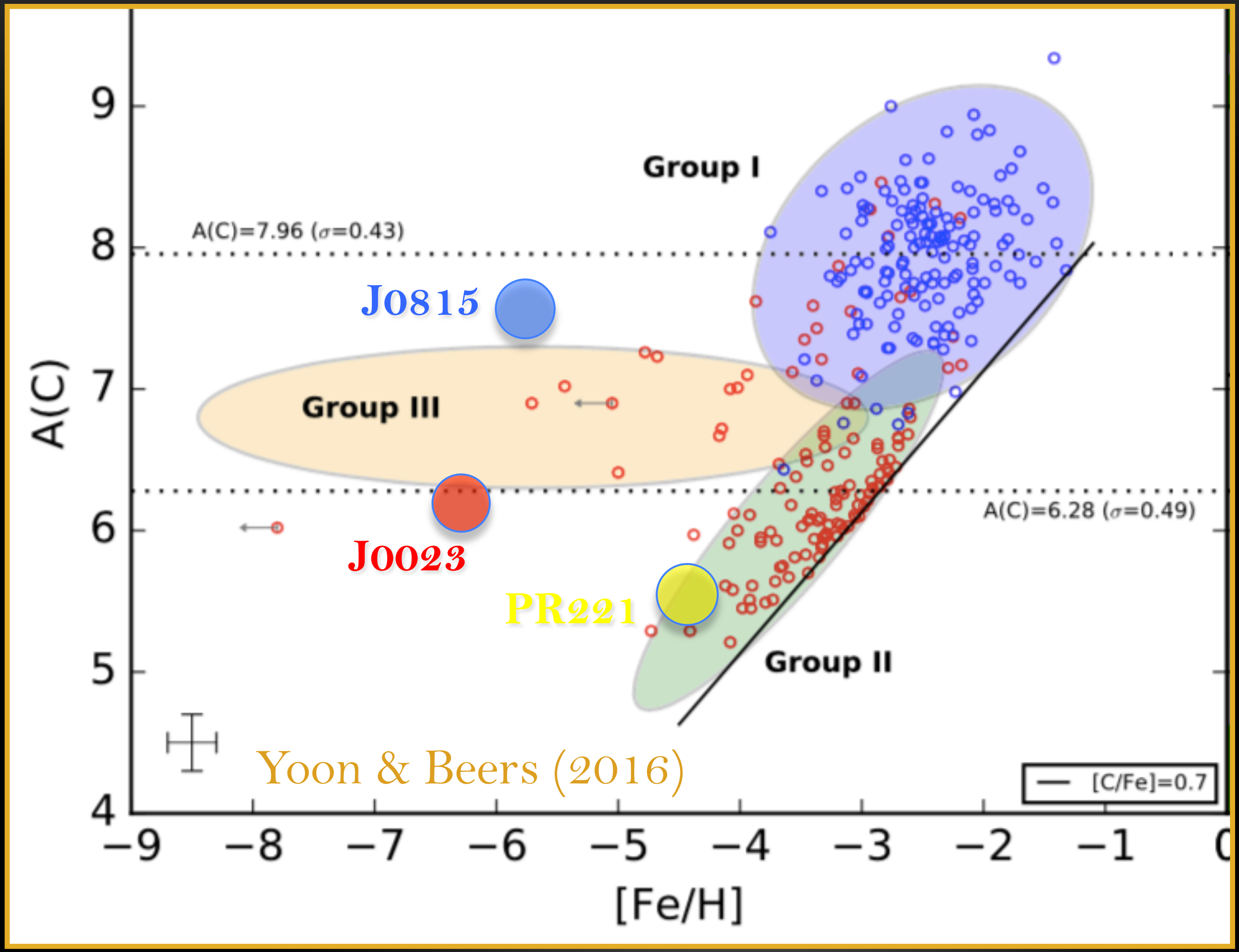
Teff ~ 5877 +- 62K
(González Hernández & Bonifacio 2009, A&A)
2MASS system (high internal consistency)

Gaia DR2 parallax :
logg ~3.5

[Fe/H] ~ - 4.7

Starkenburg, Aguado et al. (2018, MNRAS)

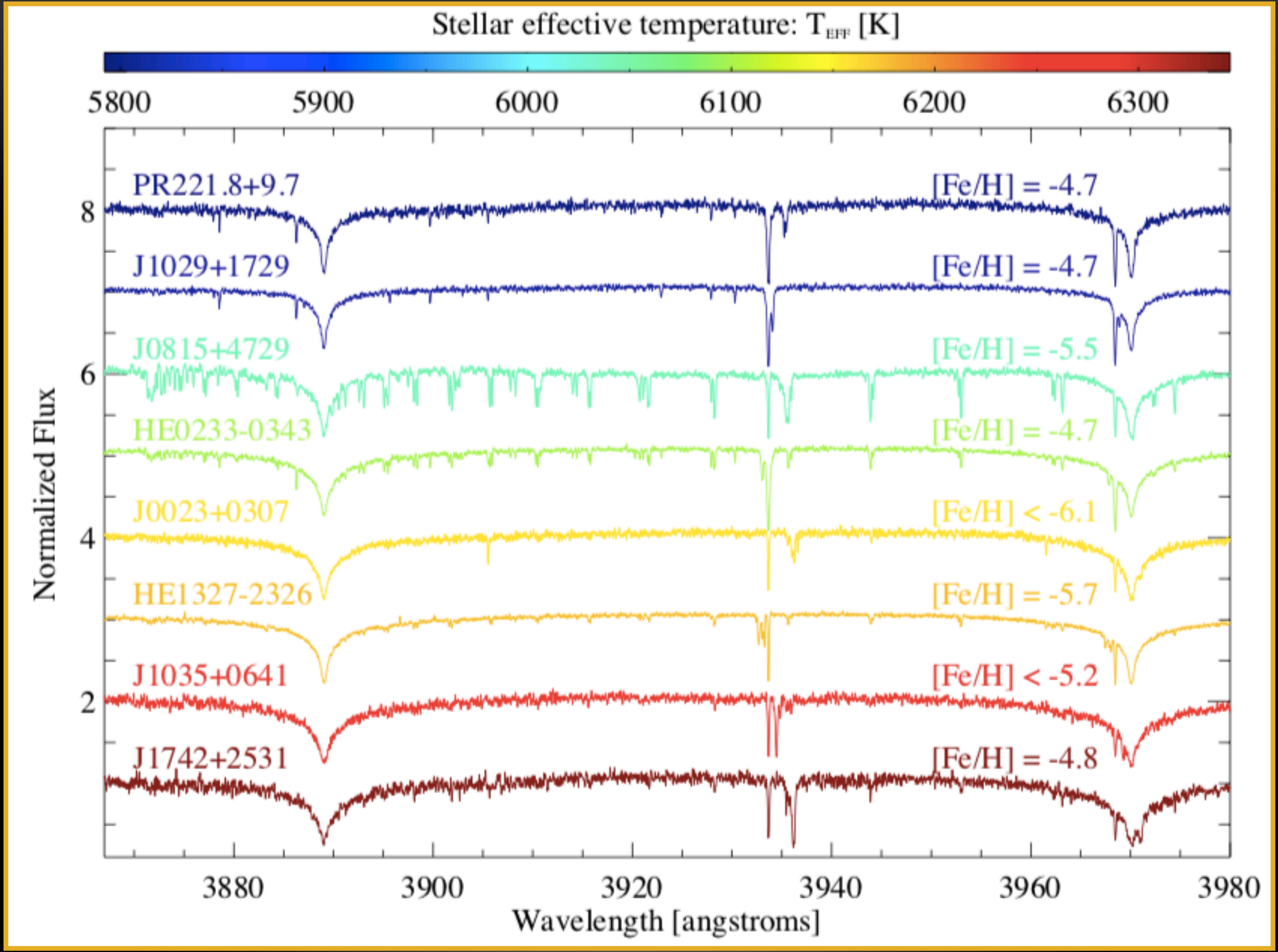
J0023: BOSS + ISIS + OSIRIS



J0023+0307: a MMP dwarf star (Fe/H] < -6.1) with the A(C) = 6.2

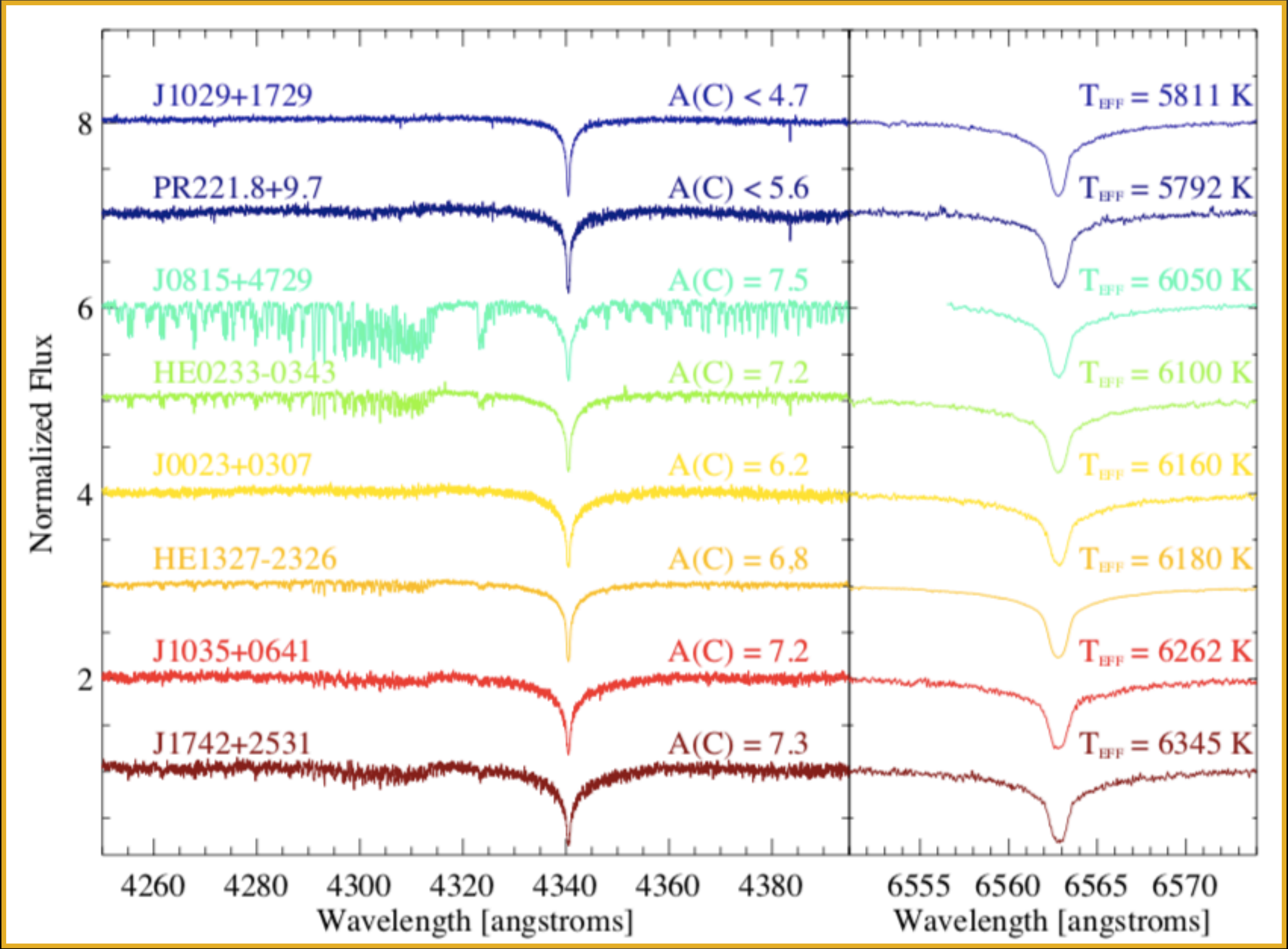
Aguado et al. (2018b, ApJ Letters; 2019, ApJ Letters)

EXTREMELY IRON POOR STARS: J0815



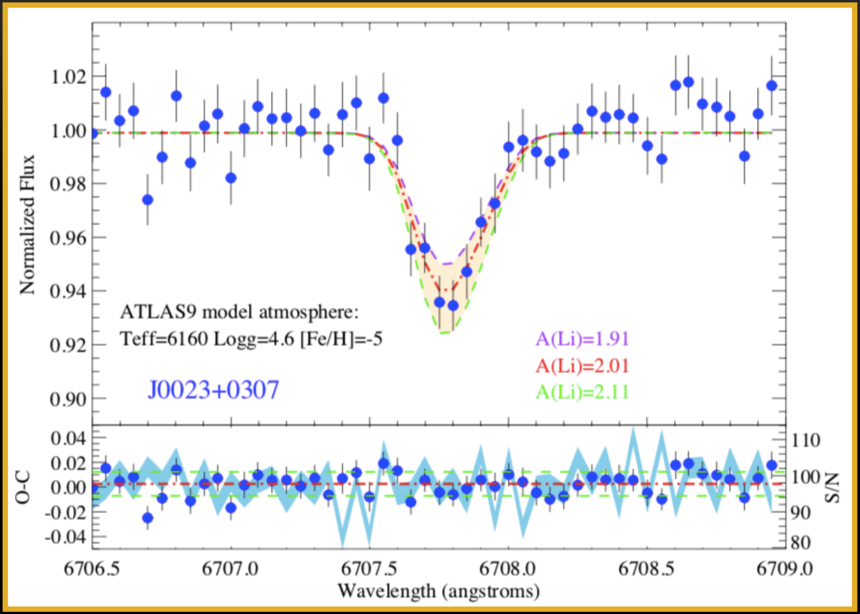
González Hernández et al. (2020, ApJ Letters)

EXTREMELY IRON POOR STARS: J0815

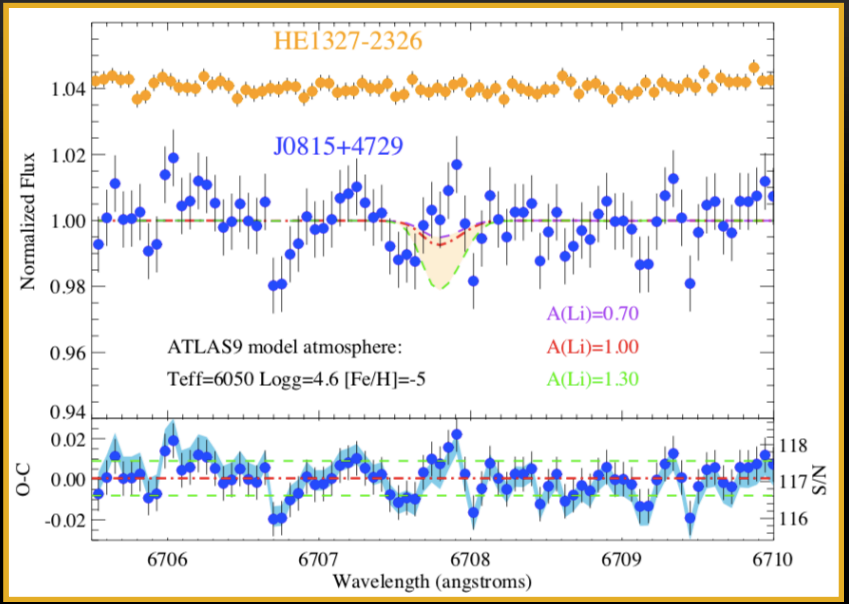


González Hernández et al. (2020, ApJ Letters)

J0023+0307: UVES SPECTRUM



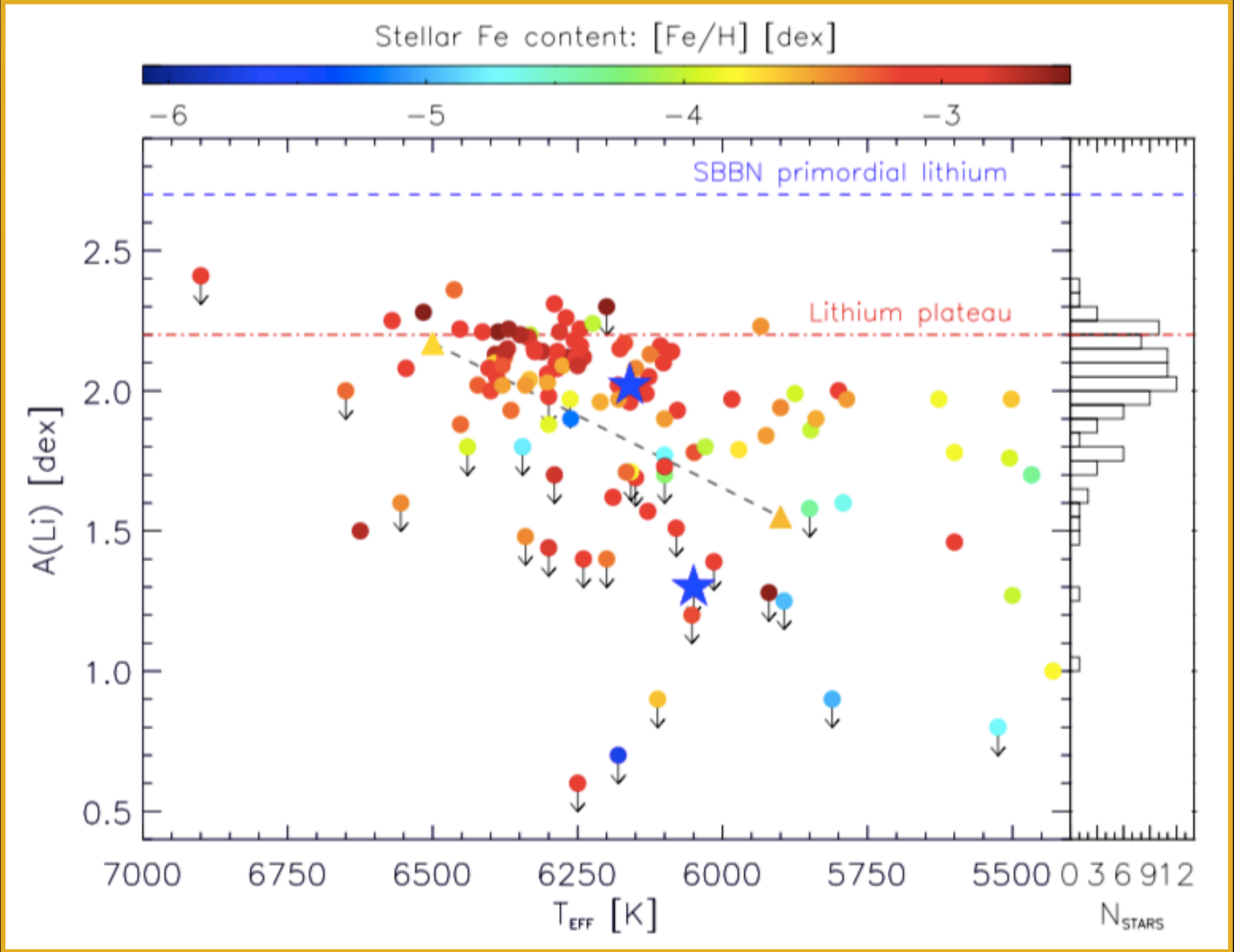
J0815+4729: HIRES SPECTRUM



J0023+0307:: Aguado et al. (2019, ApJ Letters)

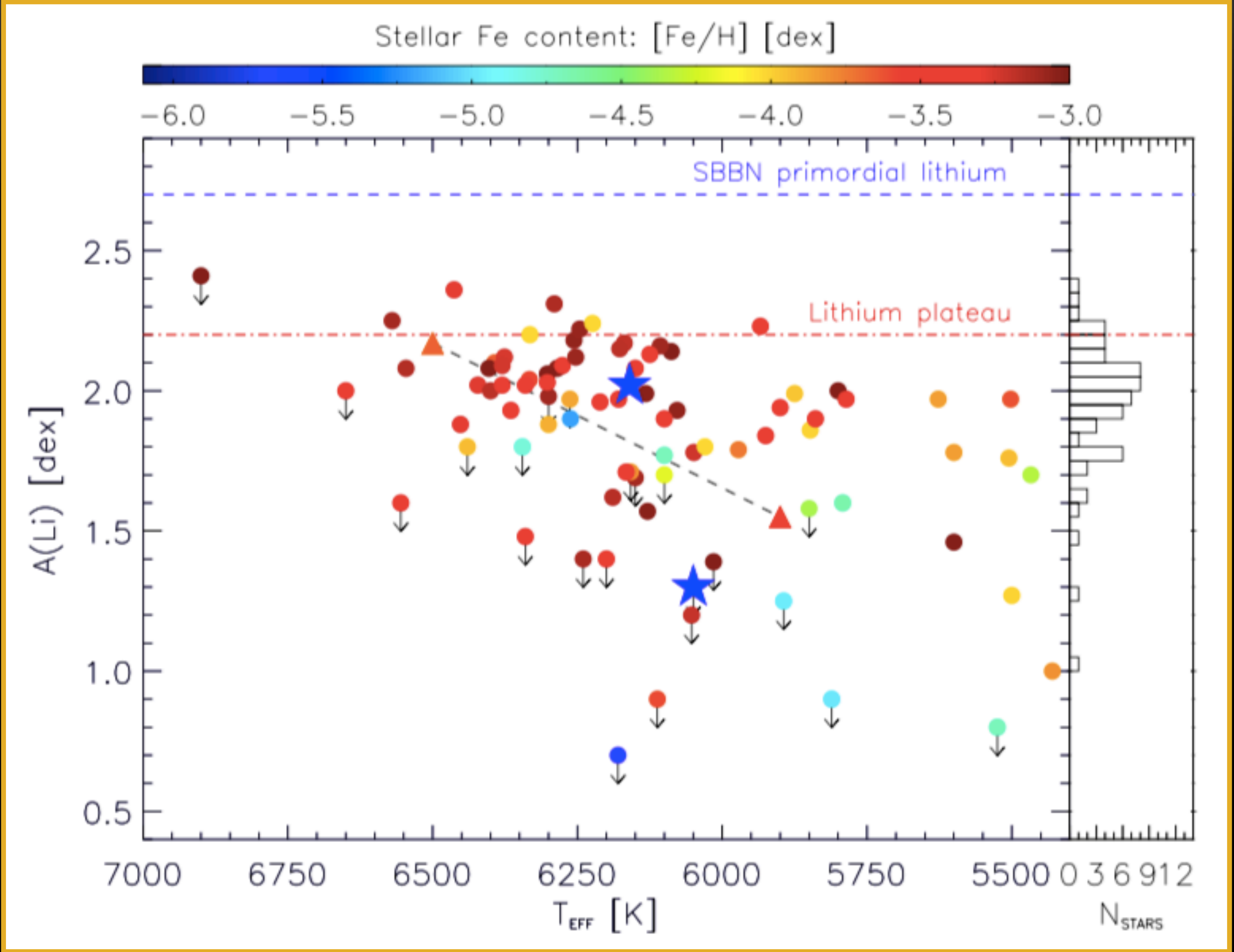
J0815+4729: González Hernández et al. (2020, ApJ Letters)

LITHIUM IN METAL POOR STARS



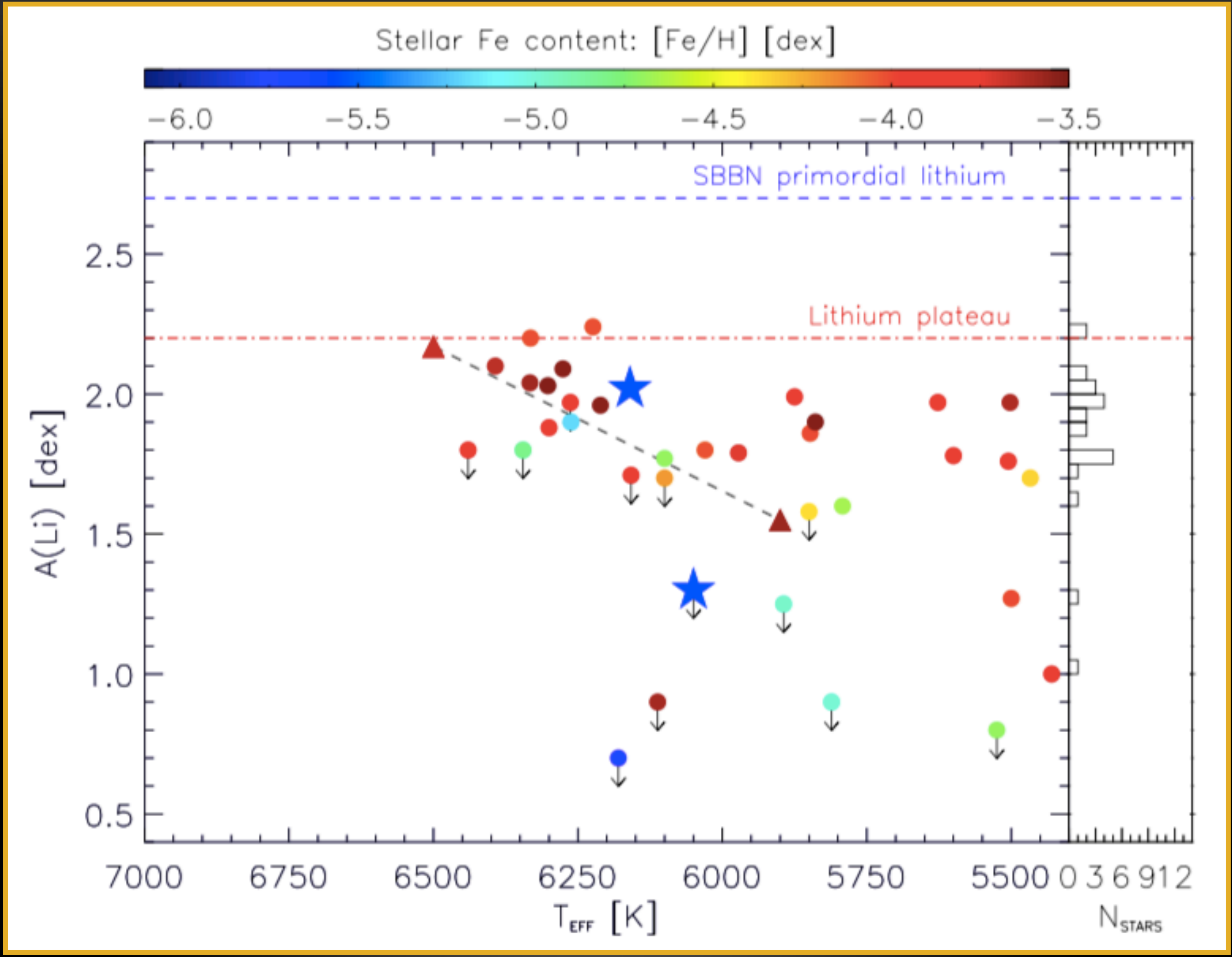
González Hernández et al. (2019, A&A; 2020, ApJ Letters)

Lithium in Metal Poor Stars



González Hernández et al. (2019, A&A; 2020, ApJ Letters)

Lithium in Metal Poor Stars



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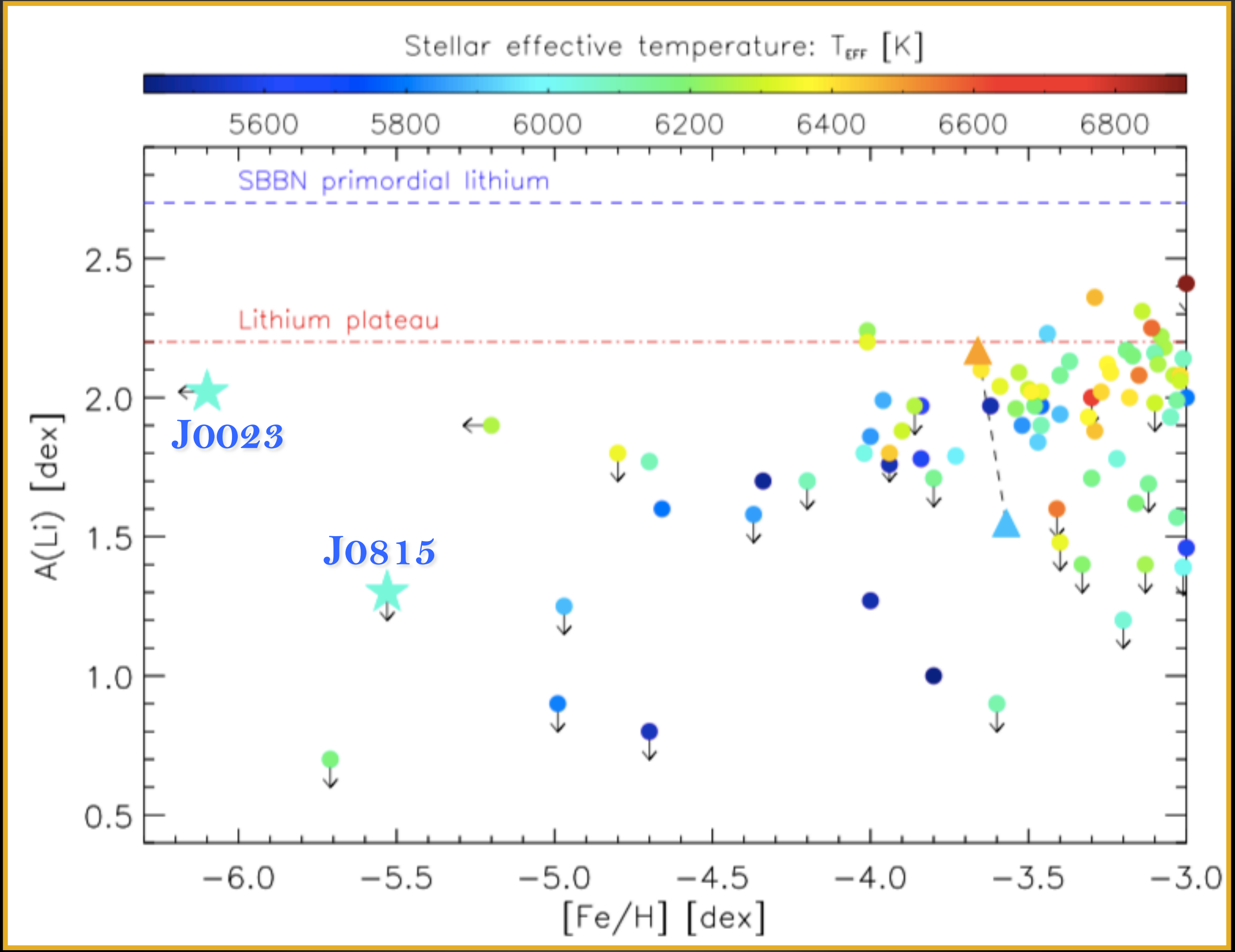
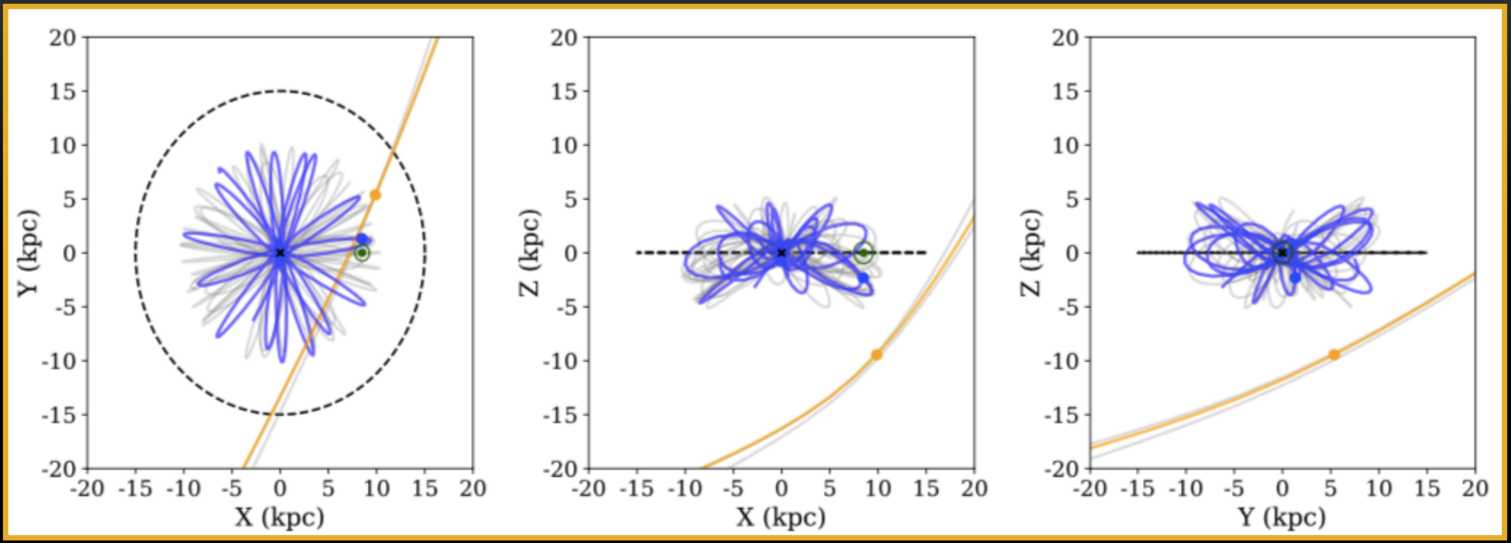
Lithium in Metal Poor Stars

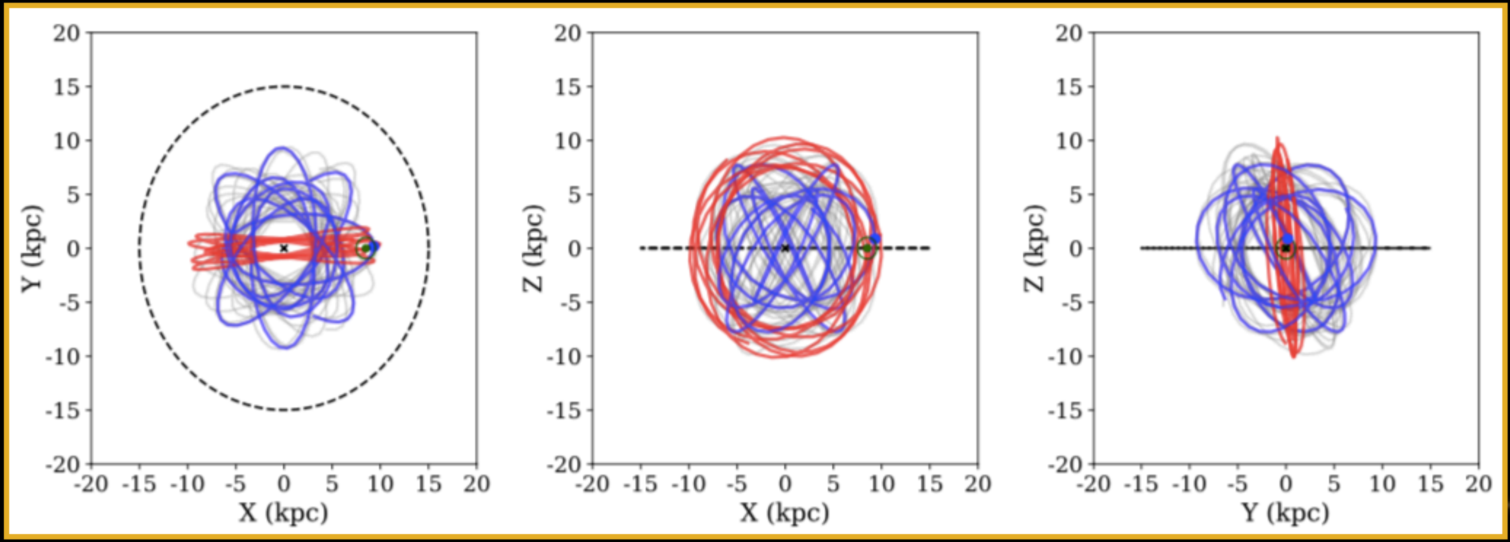


González Hernández et al. (2019, A&A; 2020, ApJ Letters)

EXTREMELY IRON POOR STARS : GALACTIC ORBITS WITH GAIA



J0023
- e=0.88
- Z< 5 kpc
- r_{apo} =9.8kpc

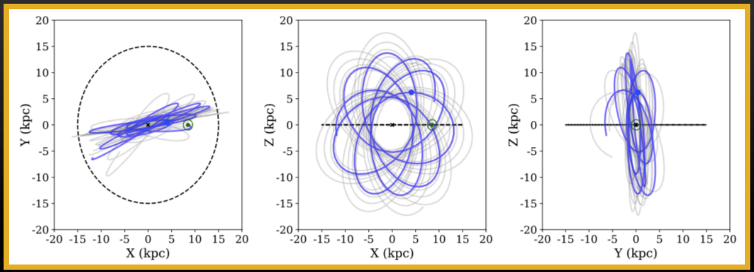


J0815
- e=0.32
- Z< 10 kpc
- r_{apo} =9.7kpc

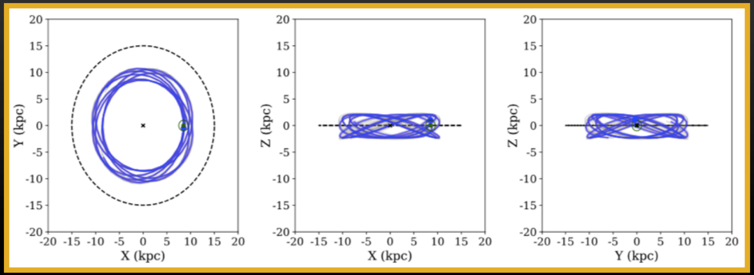
Sestito et al. (2019, MNRAS)

GAIA DR2 astrometry and photometry + published RVs + MESA isochrones + galpy +MWpot

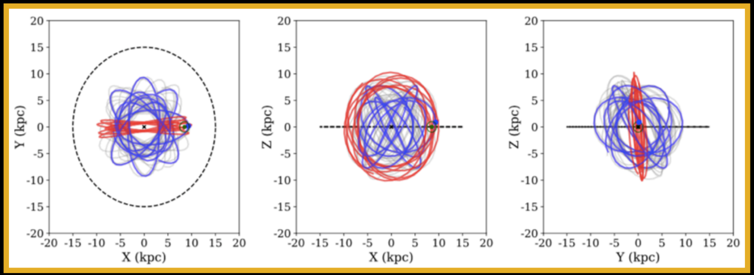
EXTREMELY IRON POOR STARS : GALACTIC ORBITS WITH GAIA



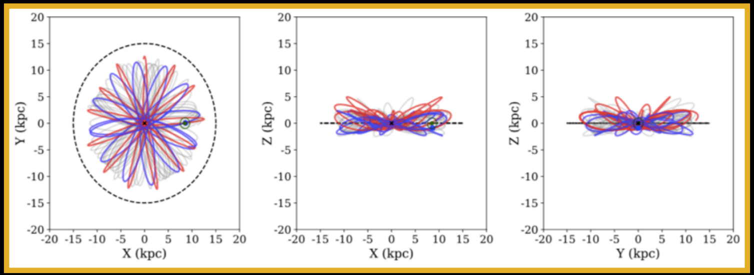
PR221



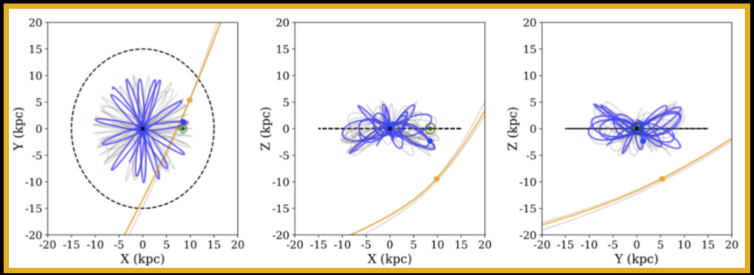
J1029



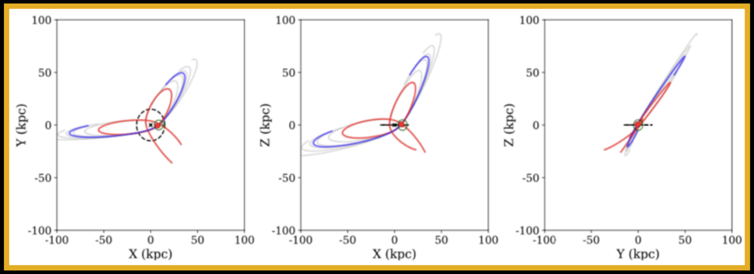
J0815



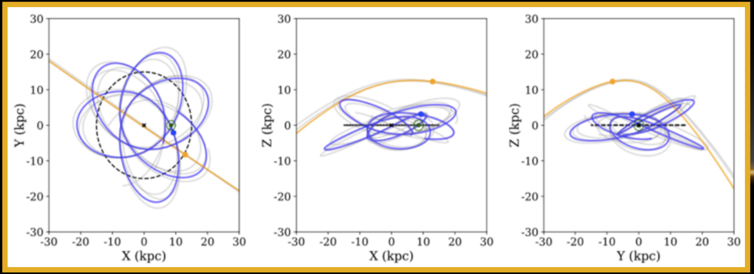
H0233



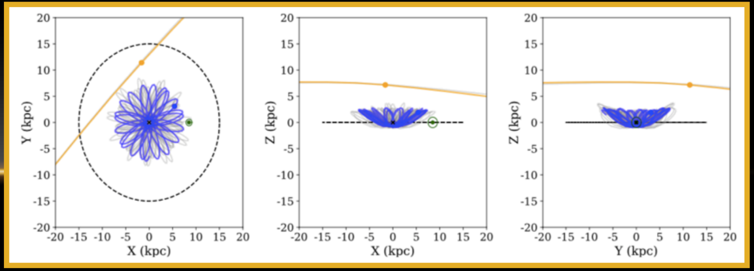
J0023



H1327



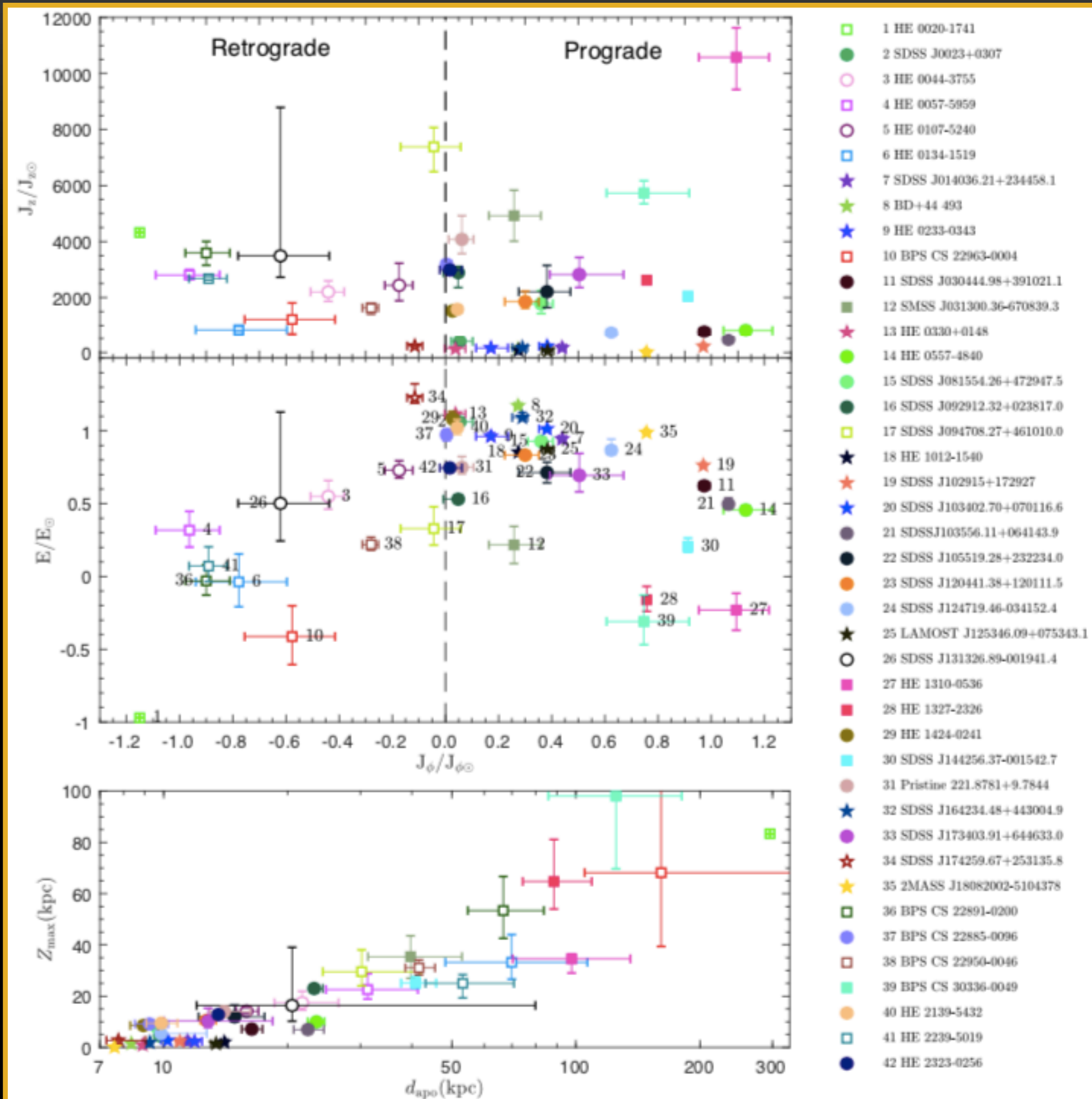
J1035



J1742

Sestito et al. (2019, MNRAS)

EXTREMELY IRON POOR STARS : GALACTIC ORBITS WITH GAIA



Sestito et al. (2019, MNRAS)

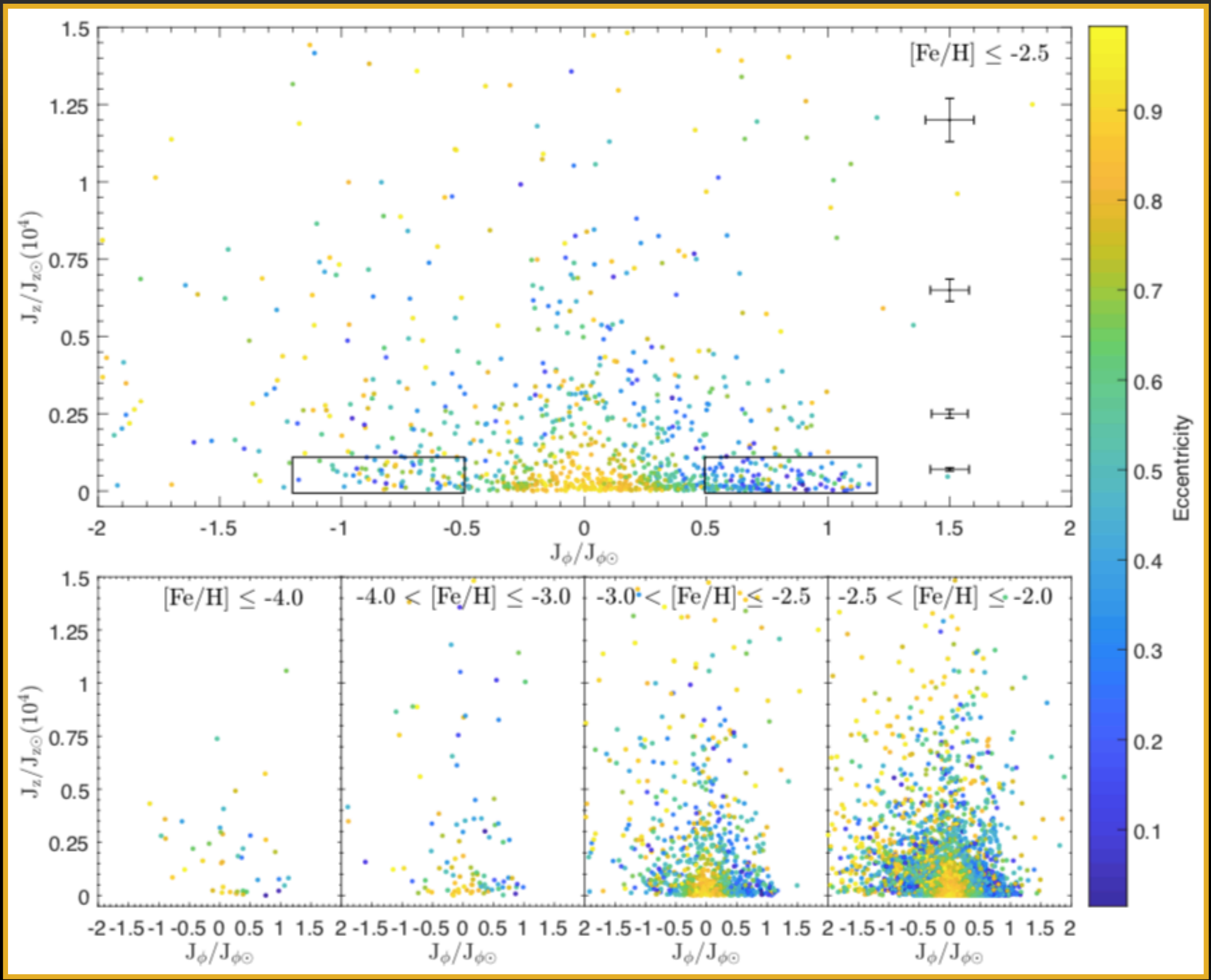
GAIA DR2 astrometry and photometry
+
published RVs
+
MESA isochrones

42 stars at [Fe/H] < -4.

~45% inner halo orbits
- apocentres < 30 kpc
~29% outer halo orbits
- apocentres > 30 kpc
~26% MW plane orbits
- Z < 3 kpc

This MW-plane UMPs are in prograde orbits except one star

Metal Poor Stars: Galactic Orbits with Gaia



PRISTINE: Aguado+19b
- 586 stars: -3<[Fe/H]<-2
- 67 stars: -4<[Fe/H]<-3
- 1 star at [Fe/H]<-4

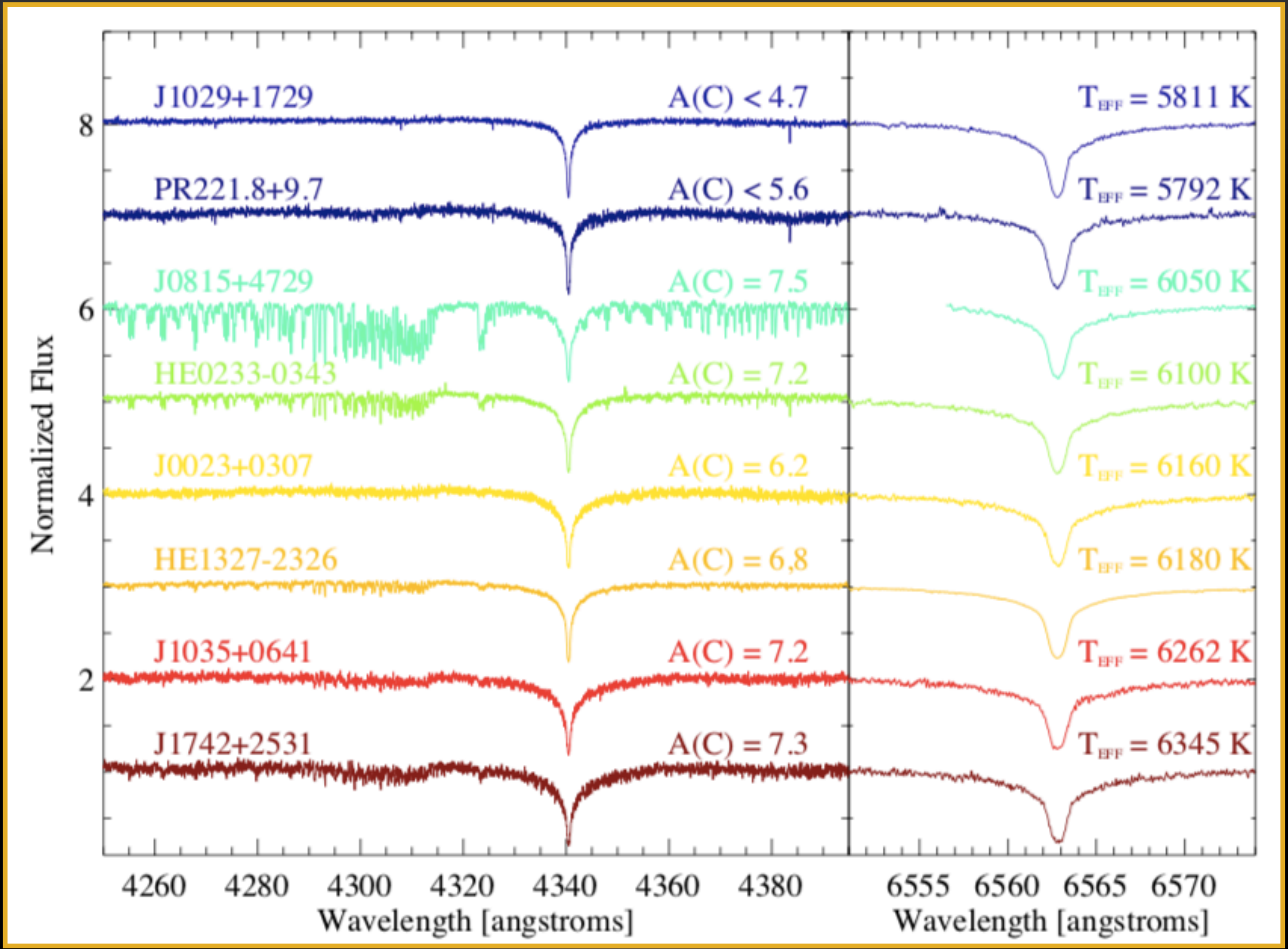
LAMOST DR3
- 4838 stars: -3<[Fe/H]<-2
- 41 stars: -4<[Fe/H]<-3

S19+Pristine+LAMOST
~31% MW plane orbits at [Fe/H] < -2.5

Most MW-plane VMPs are in prograde orbits

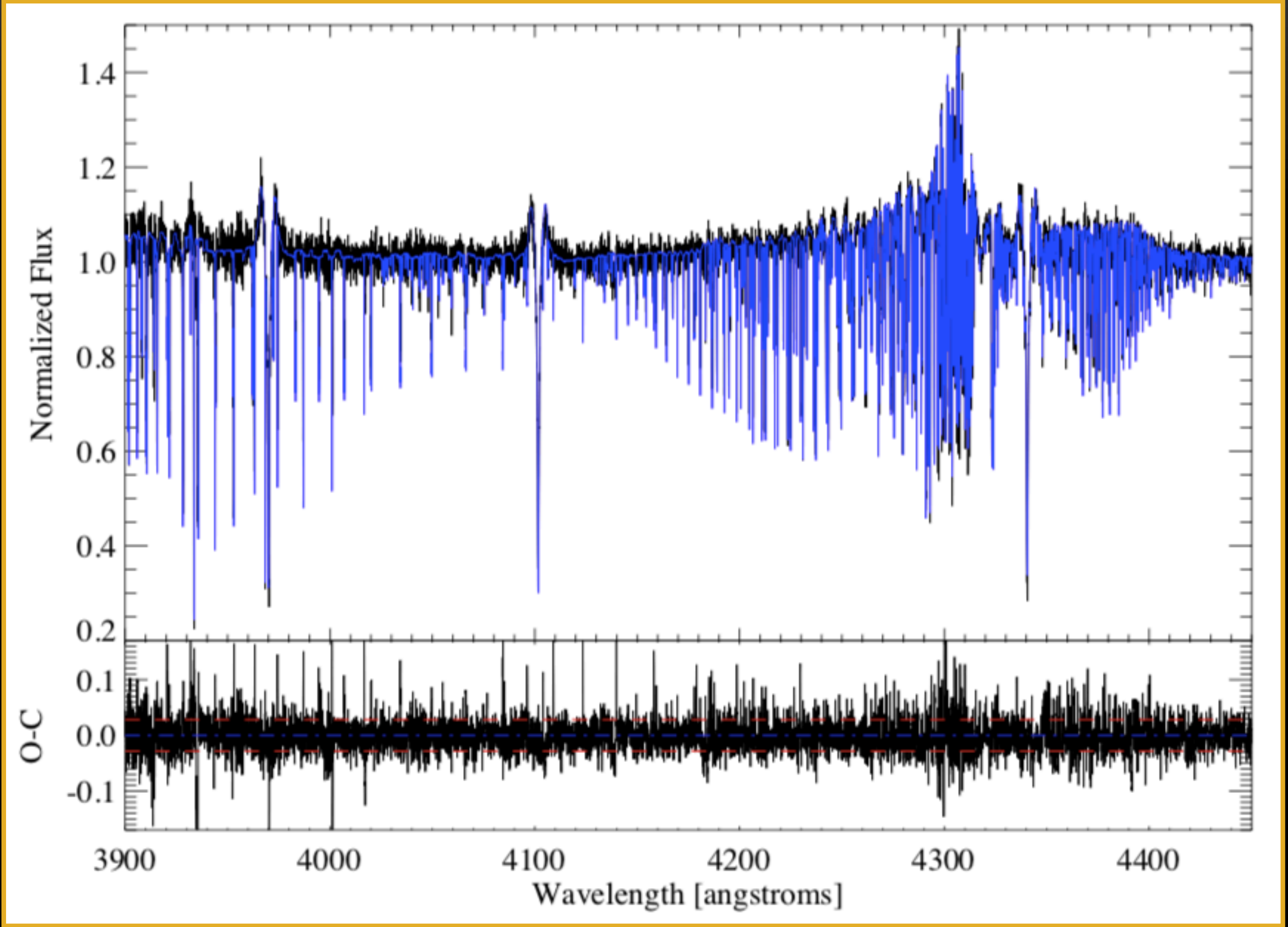
Sestito et al. (2020, MNRAS Letters)

EXTREMELY IRON POOR STARS: J0815



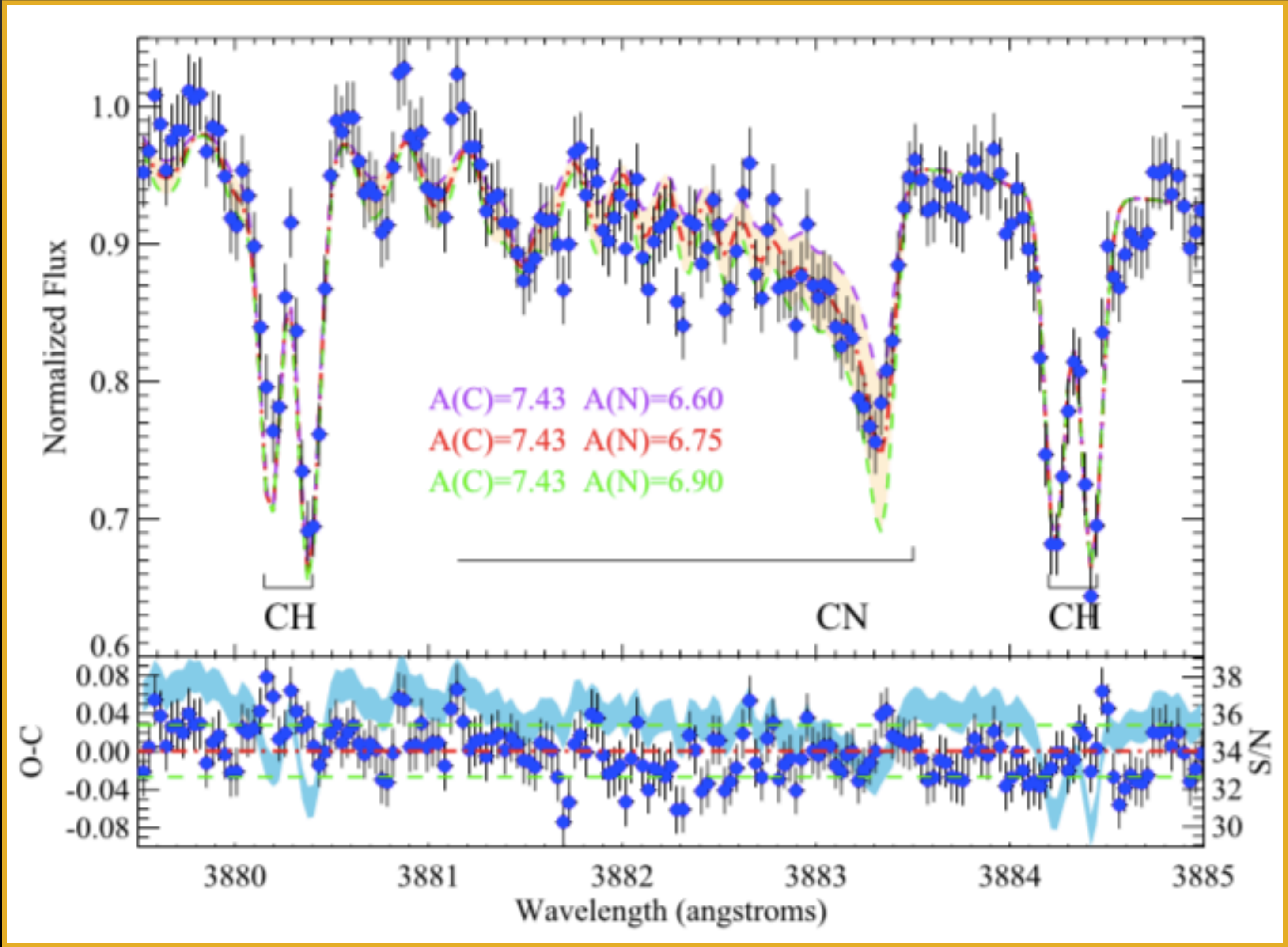
González Hernández et al. (2020, ApJ Letters)

EXTREMELY IRON POOR STARS: J0815 - CARBON



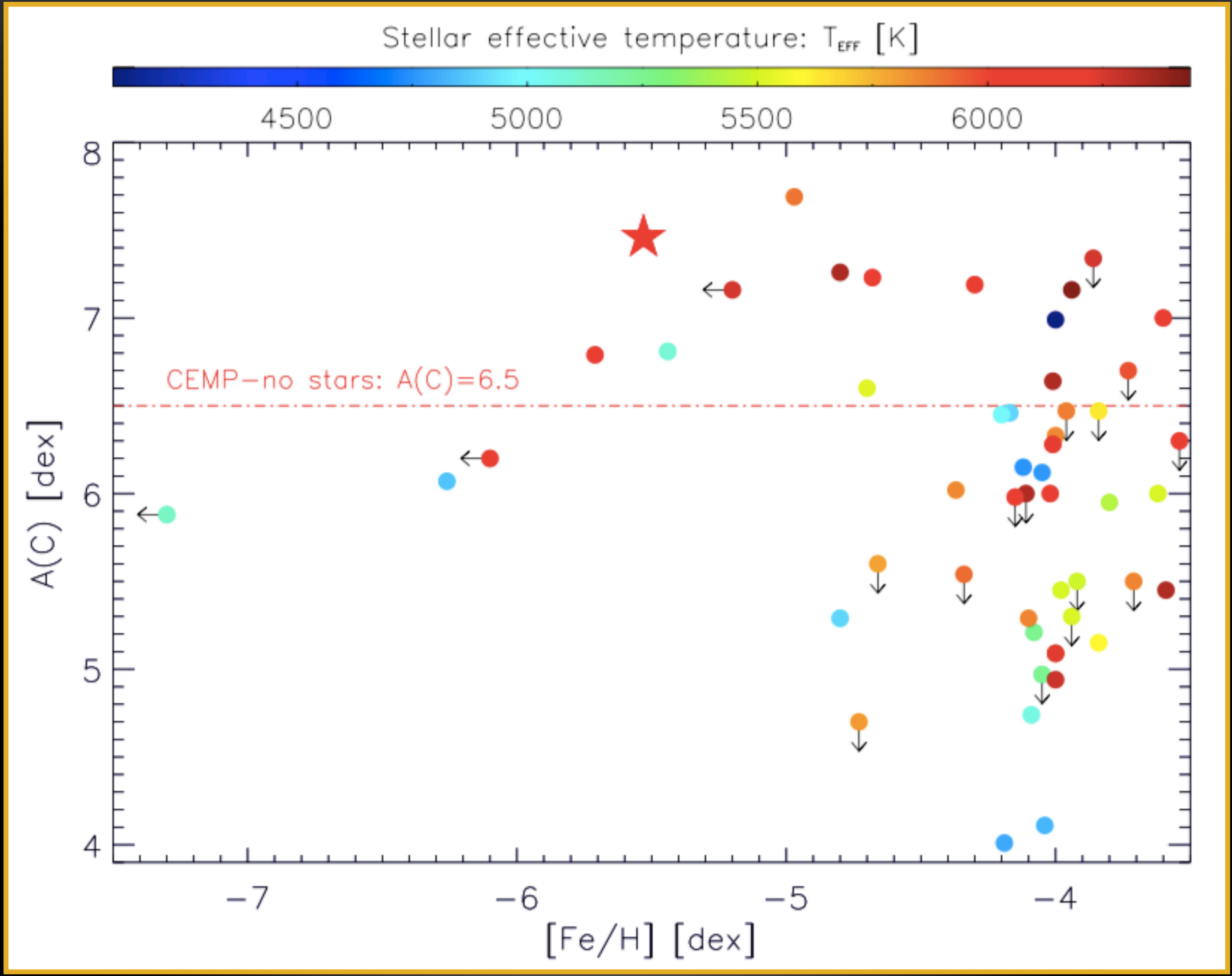
González Hernández et al. (2020, ApJ Letters)

EXTREMELY IRON POOR STARS: J0815 - NITROGEN



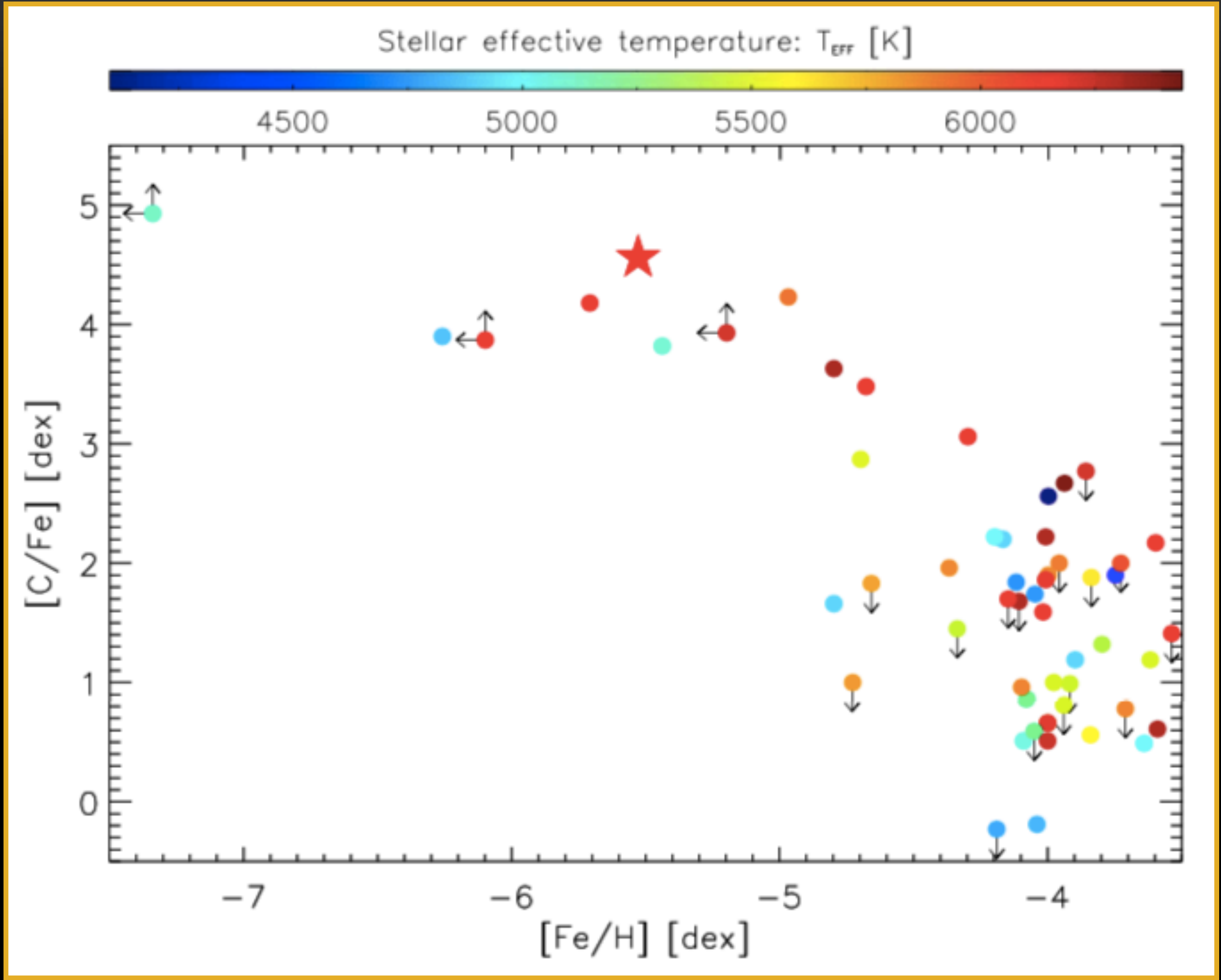
González Hernández et al. (2020, ApJ Letters)

EXTREMELY IRON POOR STARS: J0815 - CARBON



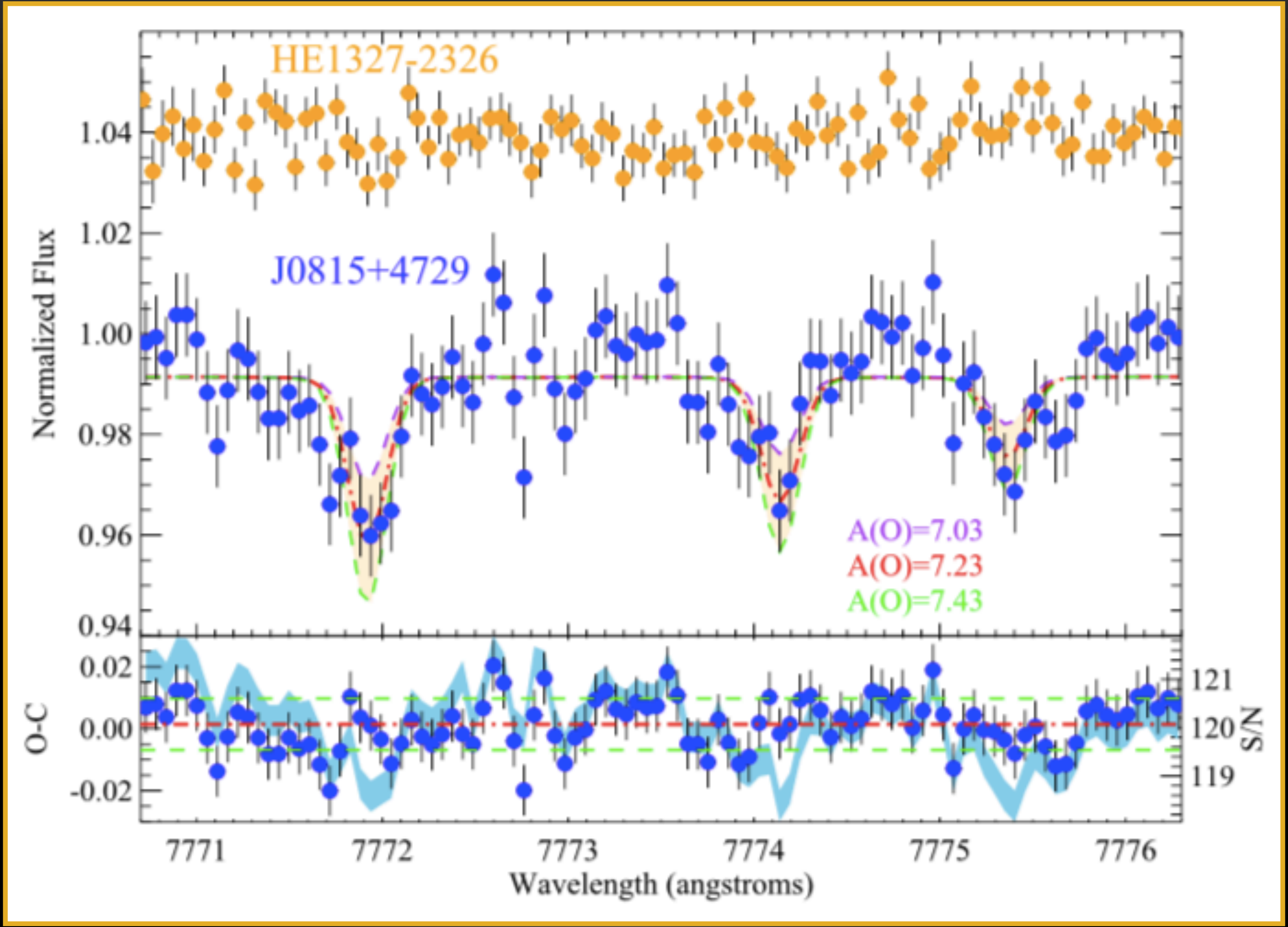
González Hernández et al. (2020, ApJ Letters)

Extremely Iron Poor Stars: J0815 - carbon



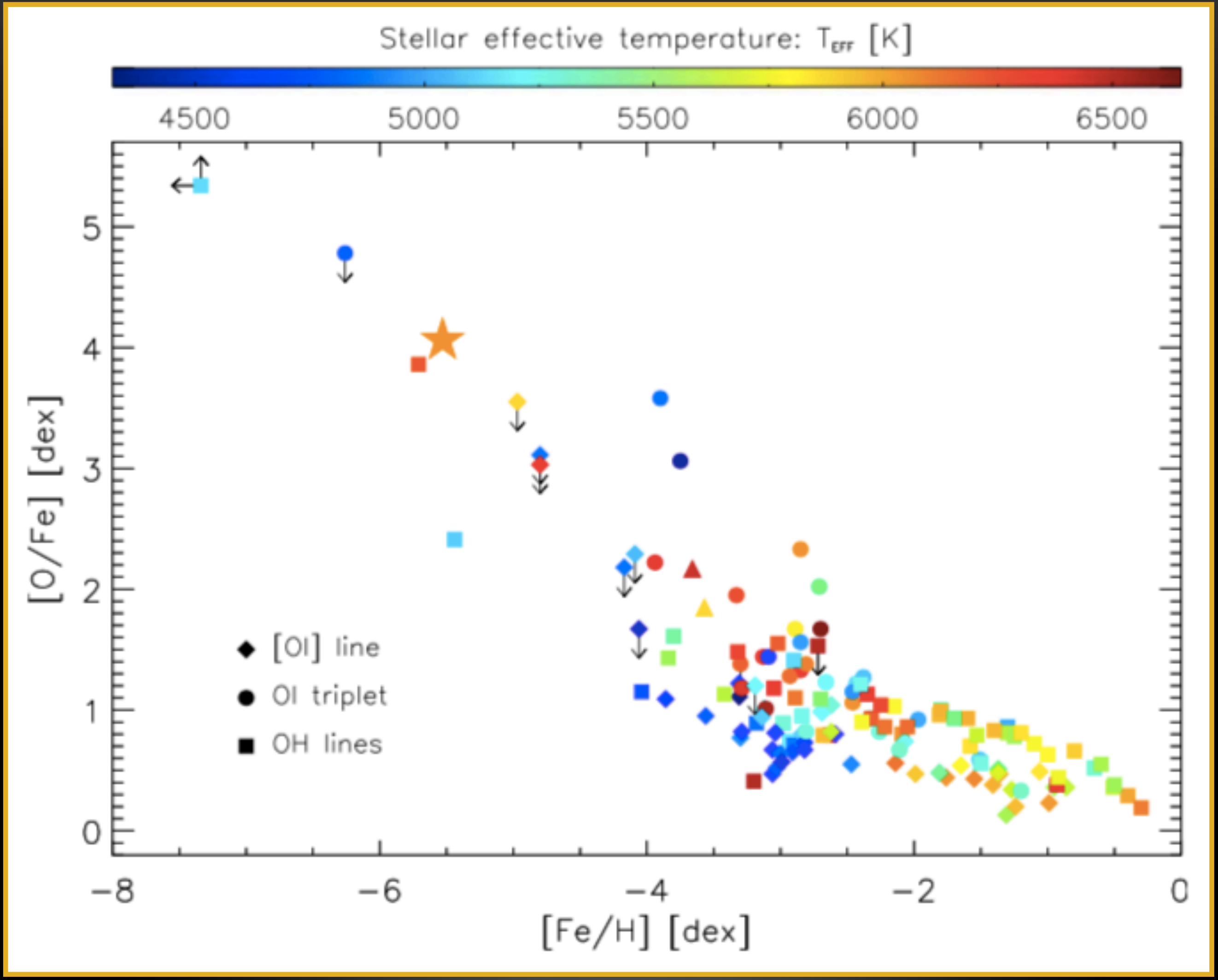
González Hernández et al. (2020, ApJ Letters)

EXTREMELY IRON POOR STARS: J0815 - OXYGEN



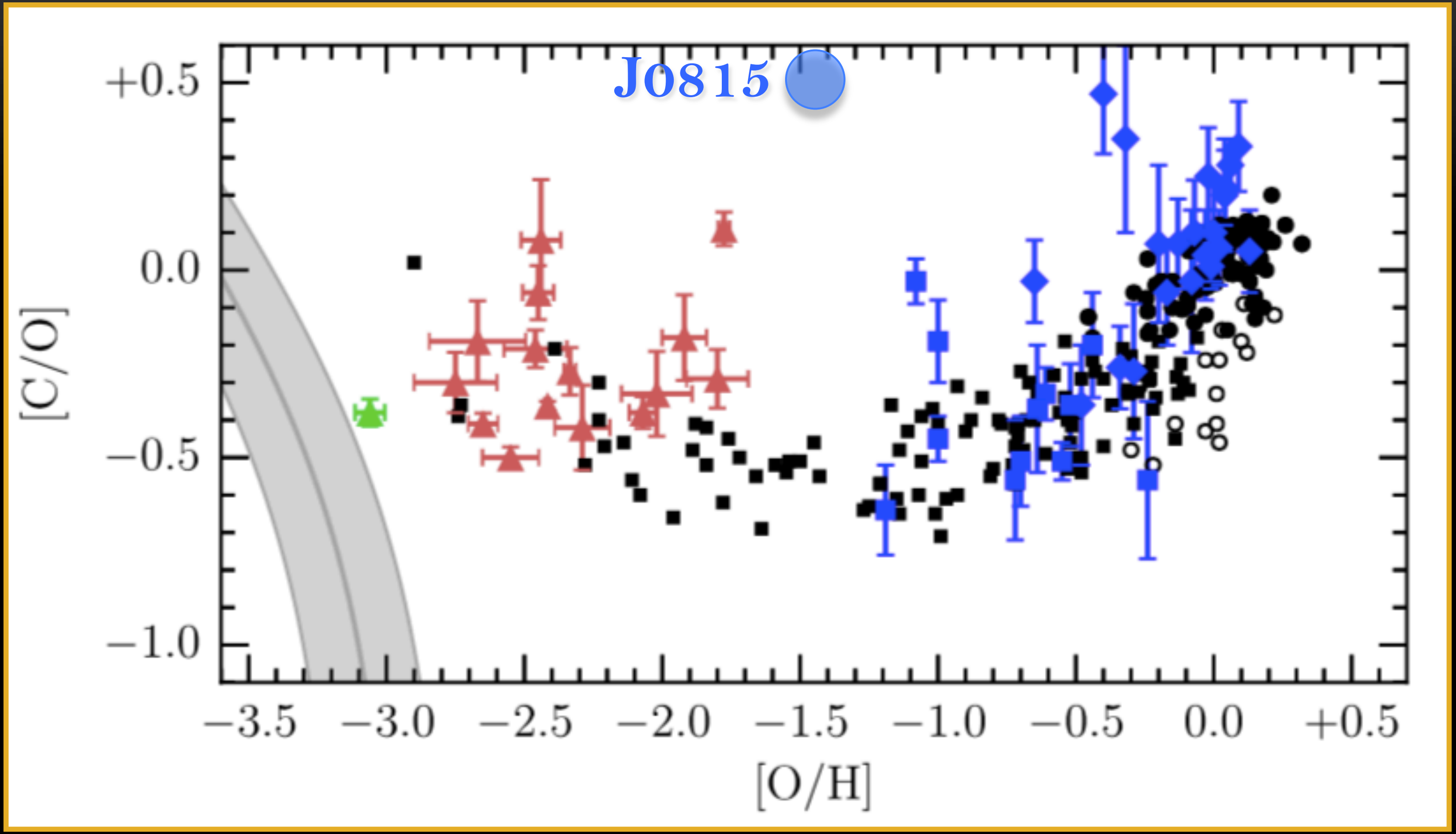
González Hernández et al. (2020, ApJ Letters)

EXTREMELY IRON POOR STARS: J0815 - OXYGEN



González Hernández et al. (2020, ApJ Letters)

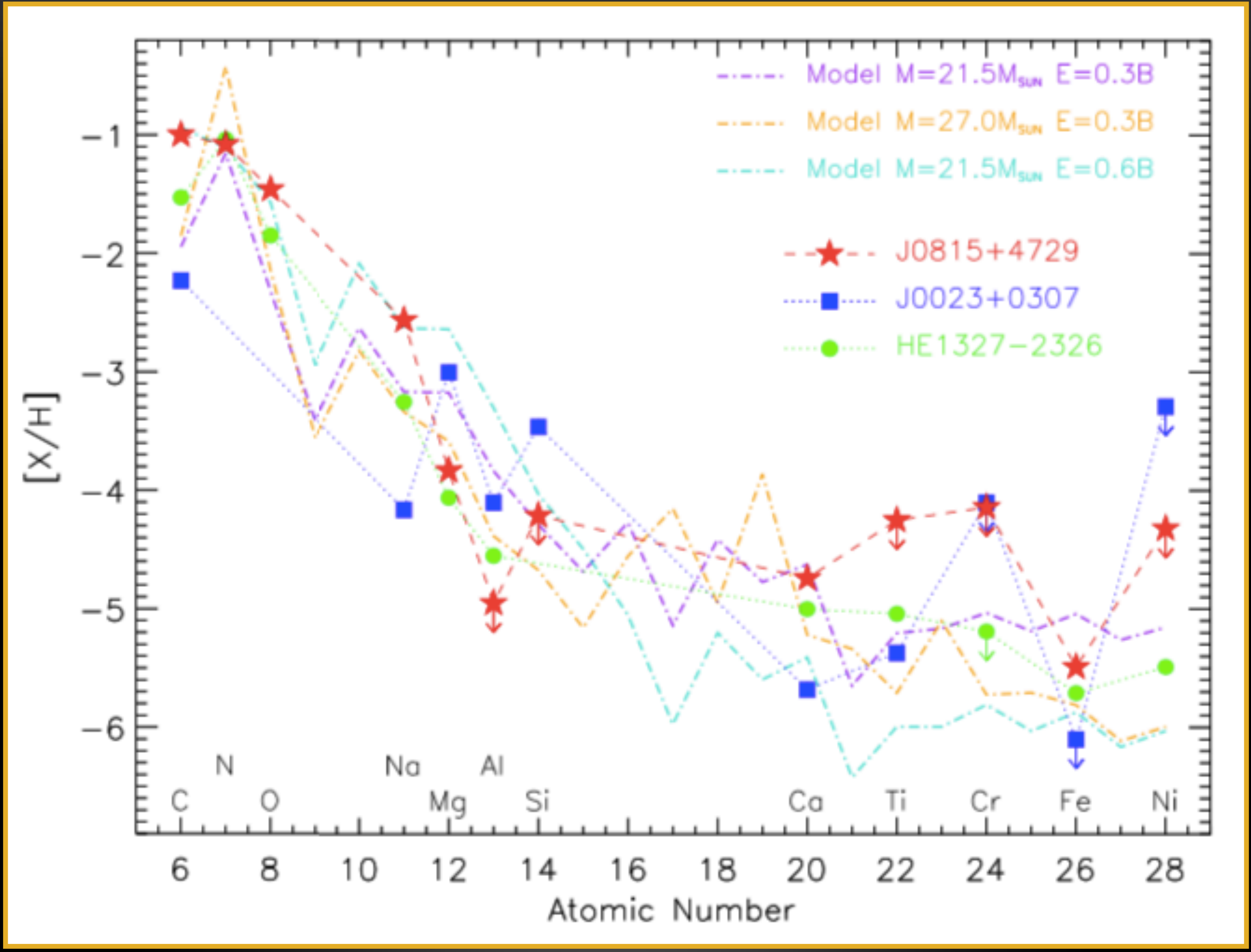
EXTREMELY IRON POOR STARS: J0815 – C/O



Cooke et al. (2017, MNRAS)

González Hernández et al. (2020, ApJ Letters)

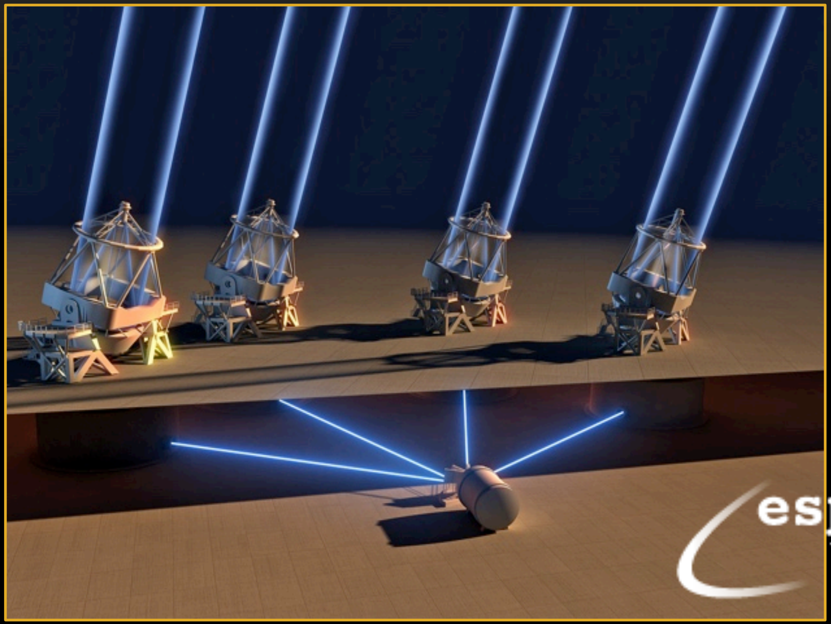
EXTREMELY IRON POOR STARS: J0815 - SNMODEL

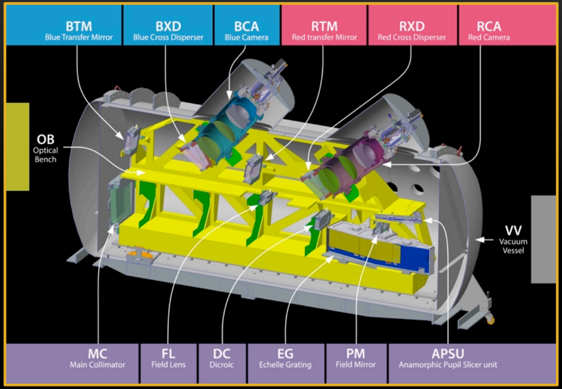


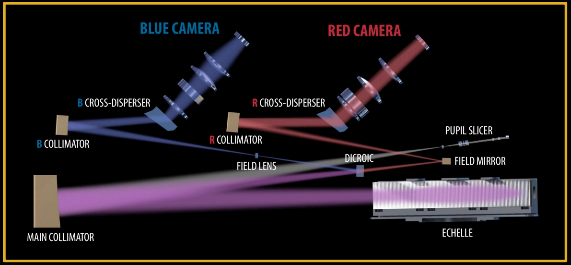
González Hernández et al. (2020, ApJ Letters)

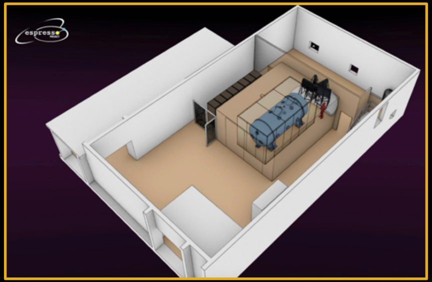
ESPRESSO

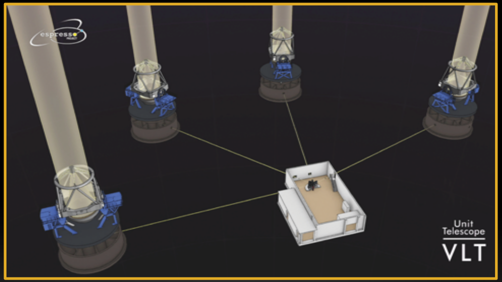
THE ECHELLE SPECTROGRAPH FOR ROCKY EXOPLANETS AND STABLE SPECTROSCOPIC OBSERVATIONS

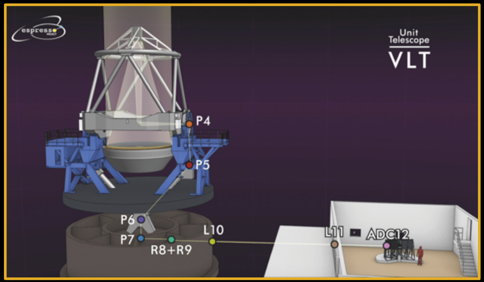












ESPRESSO :

González Hernández et al. (2018, Handbook of Exoplanets)

More info on ESPRESSO and other high-resolution spectrographs at IAC web projects:

ARES: Alta Resolución ESpectral – High Resolution Spectroscopy

FUTURE

- Searching for iron-poor stars:
  - SDSS/eBOSS, PRISTINE, HETDEX-VIRUS, J-PLUS, …
  - WEAVE@WHT, DESI, …
- Detailed chemical composition :
  - HORuS@GTC, HIRES@KeckI, HDS@Subaru, UVES and ESPRESSO@VLT (Multi-UT),
  - HRS@GTC, HIRES@ELT, TMT, GMT, …







Extremely Iron-Poor Stars and the Early Galaxy in the Context of Gaia

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Expanding the Gaia legacy: the role of Spanish ground-based facilities

Aula Magna Enric Casasses, Facultat de Físiques UB

Barcelona, 19th February 2020