Lithium in the most Iron-Poor Unevolved Stars Known and the Cosmological Lithium Problem

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Formation of First Stars

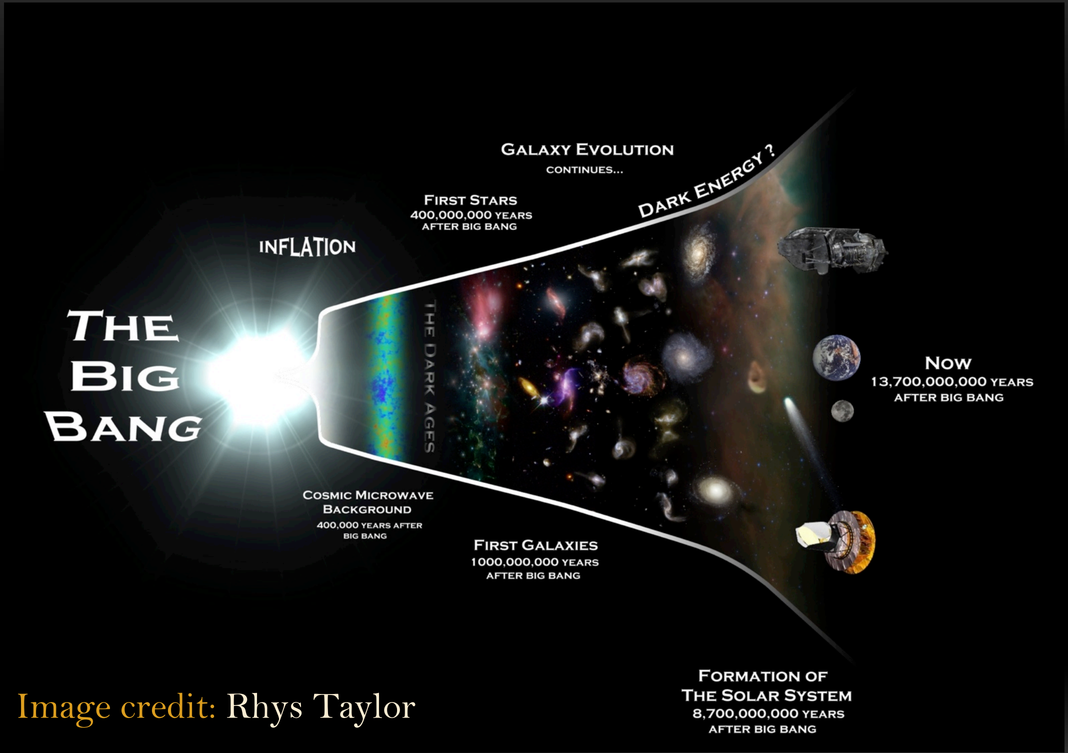


Image credit: Rhys Taylor

- SBBN : mostly H, ^{4}He, little D, ^{3}He and (very little 7Li)

- Metal-poor stars:

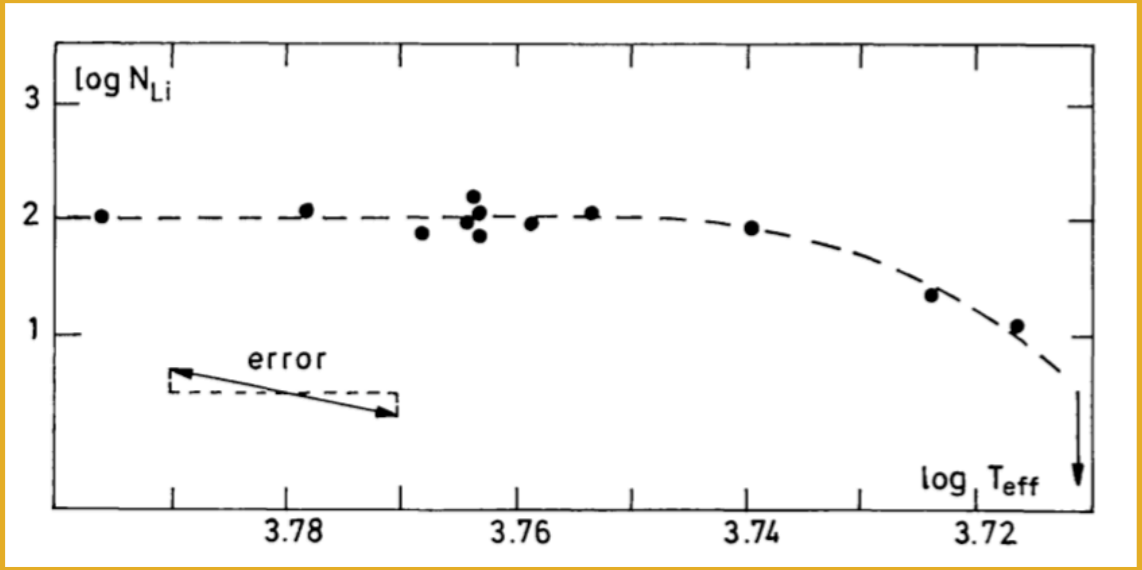
Formation and evolution in the Early Universe

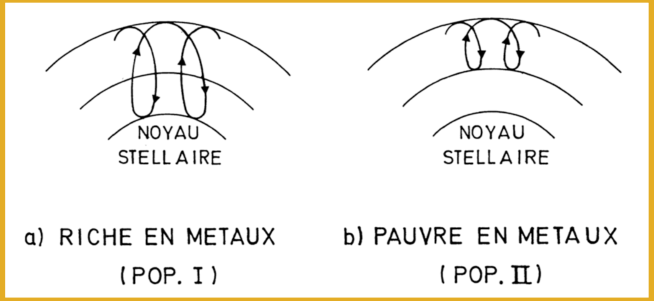
- EMP ([Fe/H] < -3)

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

Lithium in Metal Poor Stars

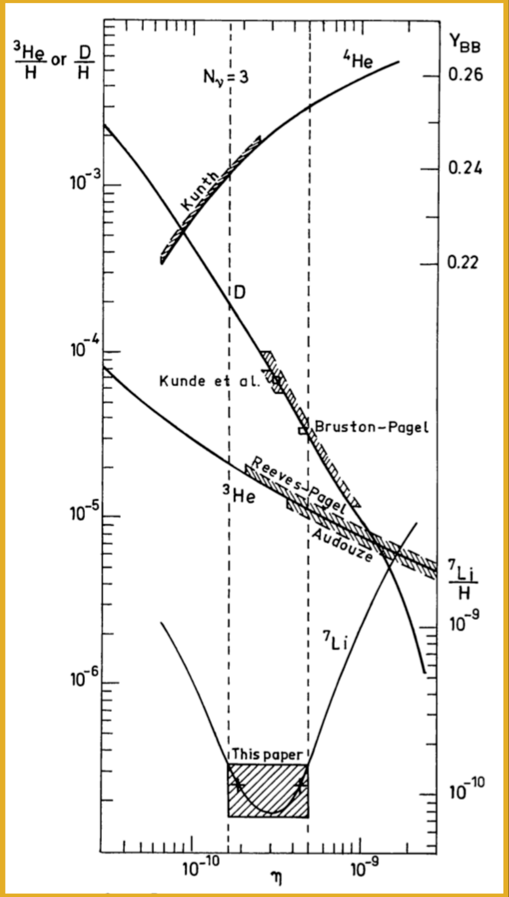




Lithium plateau

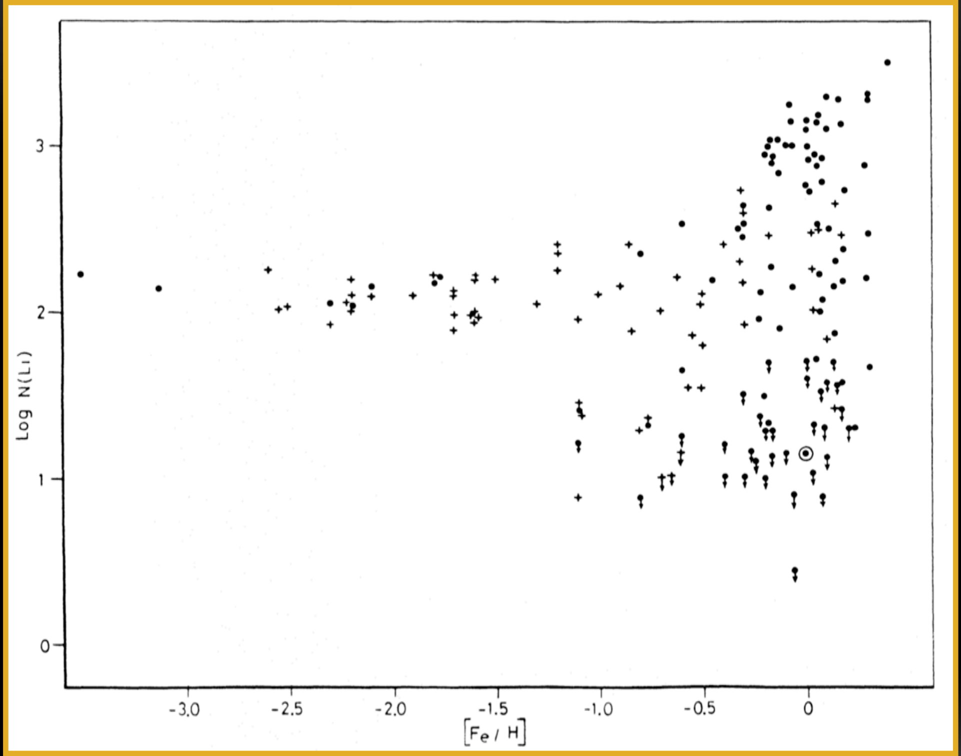
Spite & Spite (1982, Nature)

Spite & Spite (1982, A&A)



Lithium as "baryometer"

Lithium in Metal Poor Stars



Primordial Lithium abundance :

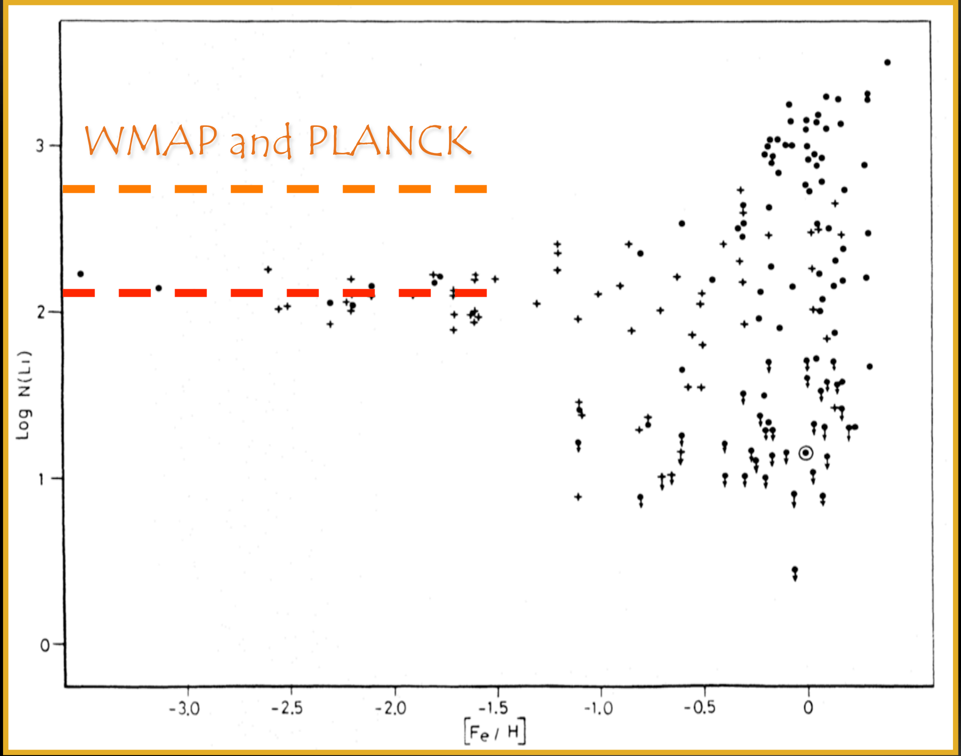
$A(\mathrm{Li}) = 2.2 \pm 0.15$

Baryon to photon ratio :

$1.5 < \eta / 10^{-10} < 5.5$

Rebolo, Molaro, & Beckman (1988, A&A)

Lithium in Metal Poor Stars



Primordial Lithium abundance :

A(Li) $= 2.2 \pm 0.15$

Baryon to photon ratio :

$1.5 < \eta / 10^{-10} < 5.5$

WMAP or PLANCK :

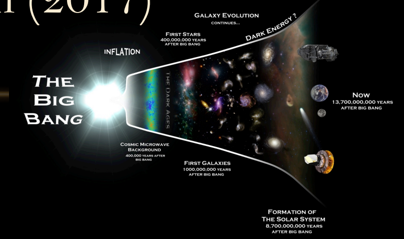
$\eta / 10^{-10} = 6.16\ (\pm 0.15)$

Komatsu et al. (2011)

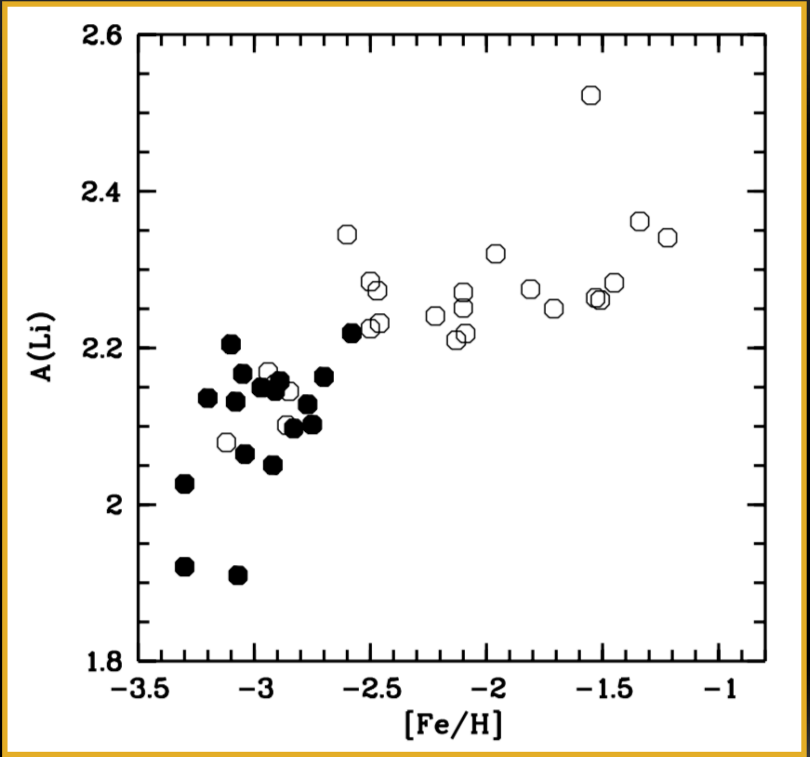
A(Li)$\sim 2.71 \pm 0.04$

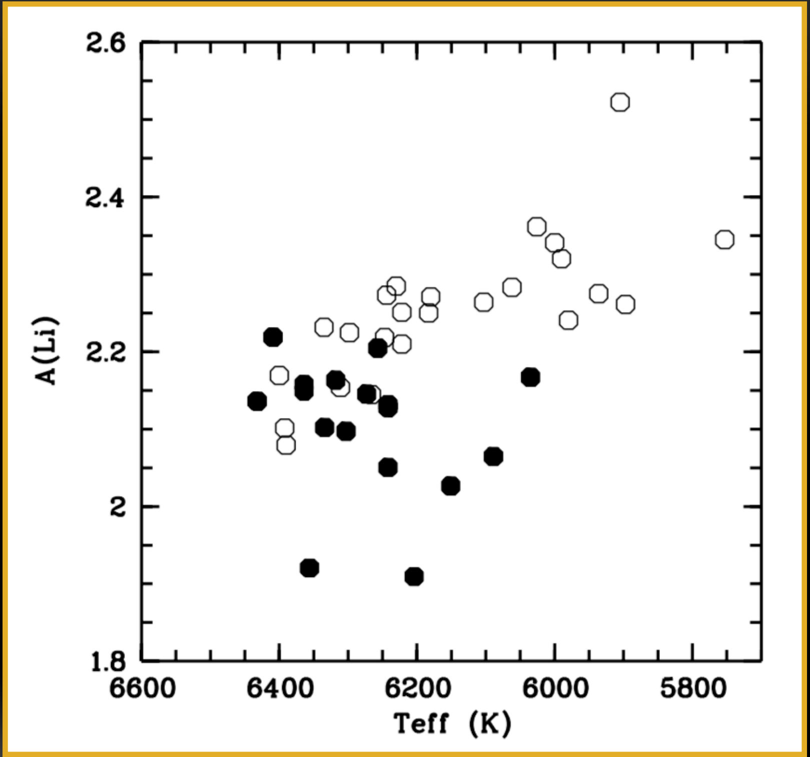
Coc & Vangioni (2017)

Rebolo, Molaro, & Beckman (1988, A&A)



Lithium in Metal Poor Stars

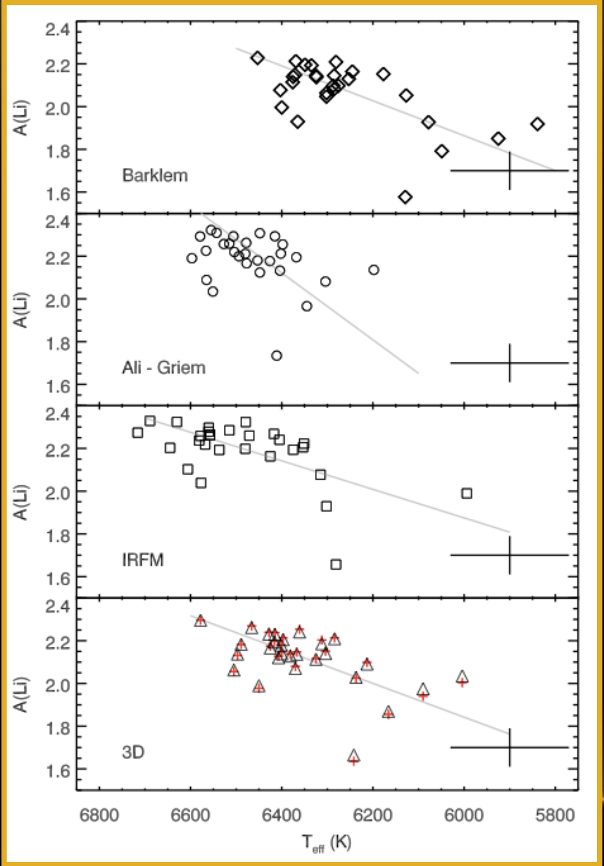




Bonifacio et al. (2007, A&A)

-3.3 < [Fe/H] < -1.2

Lithium in Metal Poor Stars

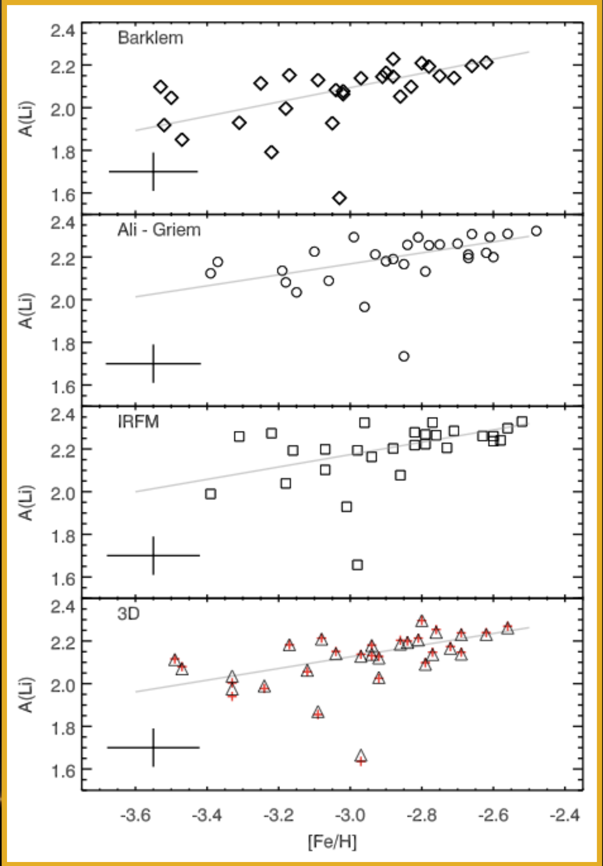


1D Hα Barklem

1D Hα Ali-Griem

IRFM: **González Hernández & Bonifacio (2009, A&A)**

3D Hα: **Ludwig et al. (2009)**



Sbordone et al. (2010, A&A)

Lithium Discrepancy

The 0.4-0.5 dex difference between the Spite plateau and WMAP & PLANCK results :

- Diffusion with turbulence (Richard et al. 2005)
- Gravity waves in stellar interiors (Charbonnel & Talon 2005)
- Pre-galactic Li processing by massive Pop III stars (Piau et al. 2006)
- Tachocline mixing (Piau et al. 2008)
- Mass dependence Li depletion (Meléndez et al. 2010)
- Pre-main sequence depletion + accretion (Molaro et al. 2012)
- Non-standard BBN (Jedamzik 2006; Hisano 2009)

Lithium in Metal Poor Stars

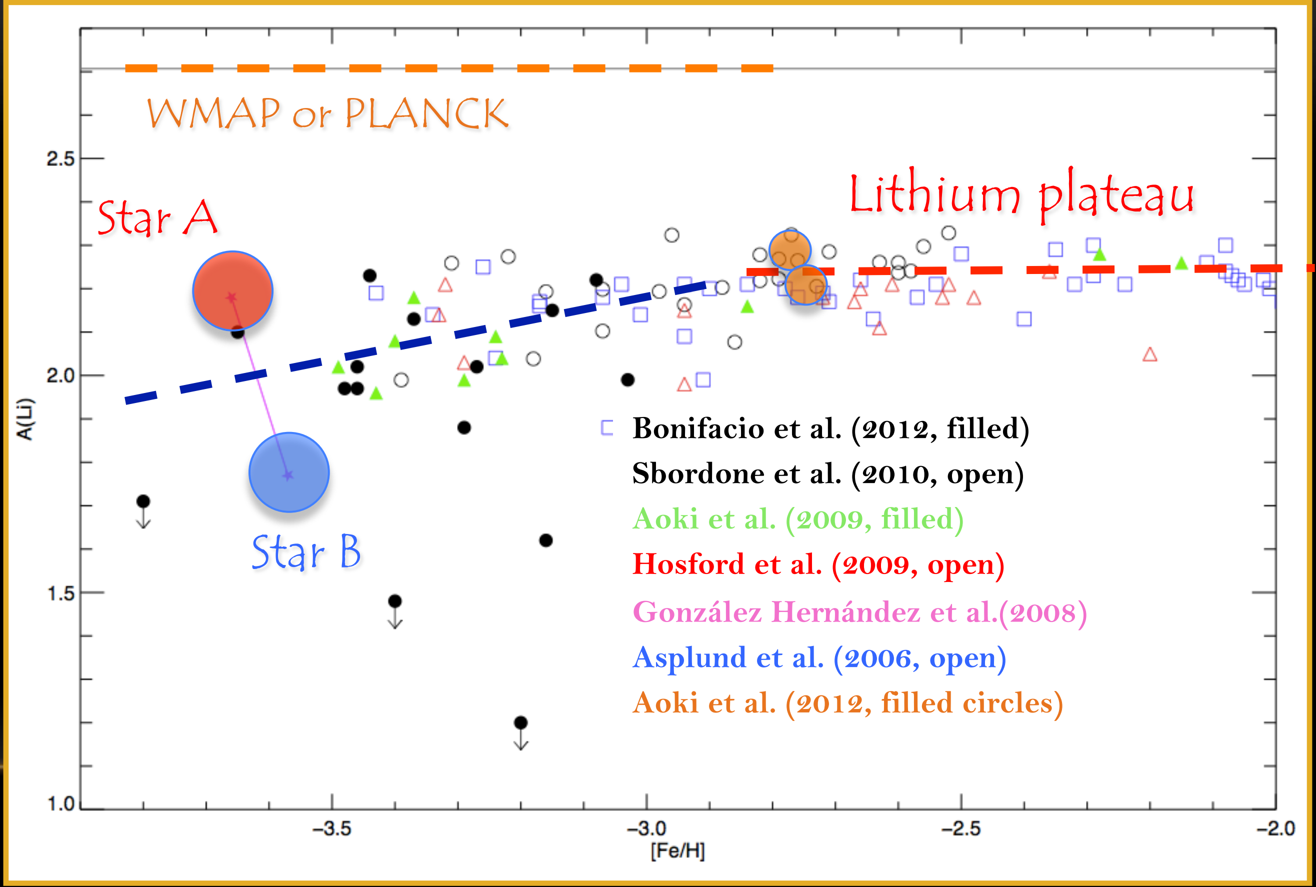
WMAP or PLANCK :

(A(Li)~2.71 ± 0.04

Coc & Vangioni 2017)

-3.8 < [Fe/H] < -2.0

Sbordone et al. (2012, MSAI)

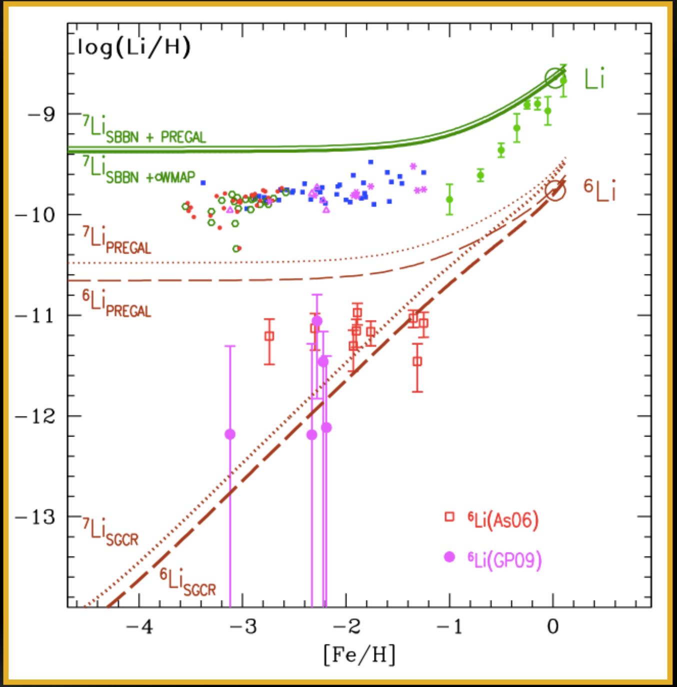


LITHIUM DISCREPANCY : ^{6}LI

- BBN produces insignificant amout of ^{6}Li
- ^{6}Li in the Galaxy possibly created by spallation reactions with galactic cosmic rays (GCRs)
- At [Fe/H] < -2: predicted level of ^{6}Li/^{7}Li < 1%
- Detecting ^{6}Li in metal-poor stars may suggest other production channels:

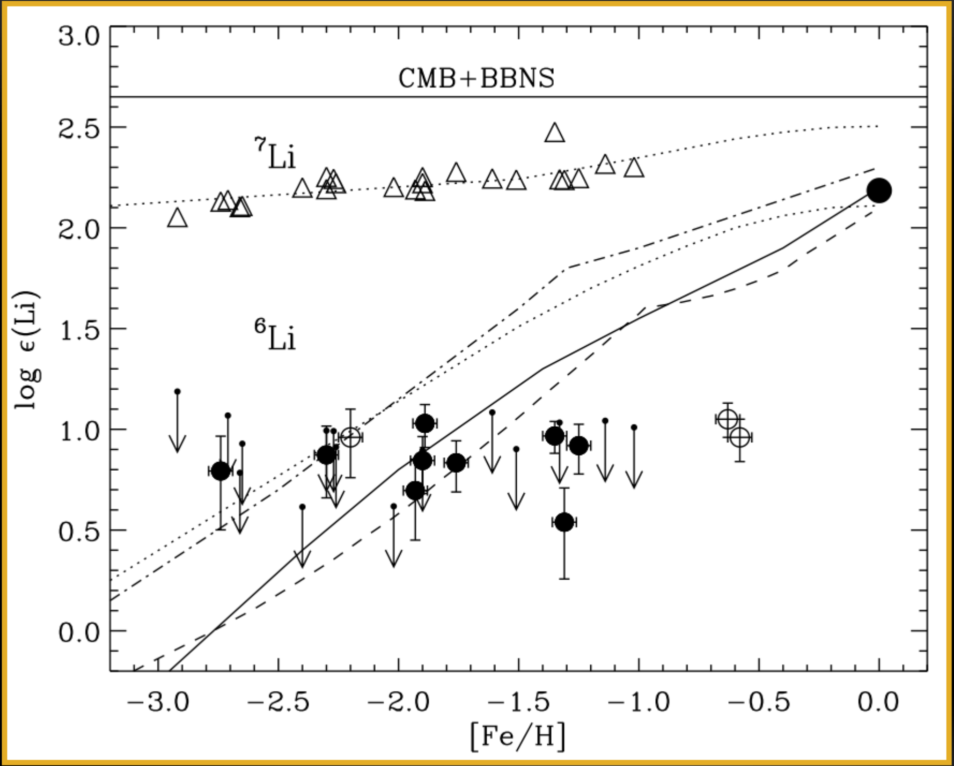
- non-standard physics (Jedamzik & Pospelov 2009)

- pre-galactic origin (e.g. Rollinde et al. 2006)



Prantzos et al. (2012)

Lithium in Metal Poor Stars



- ^{7}Li plateau
- ^{6}Li plateau ?

From SBBN :

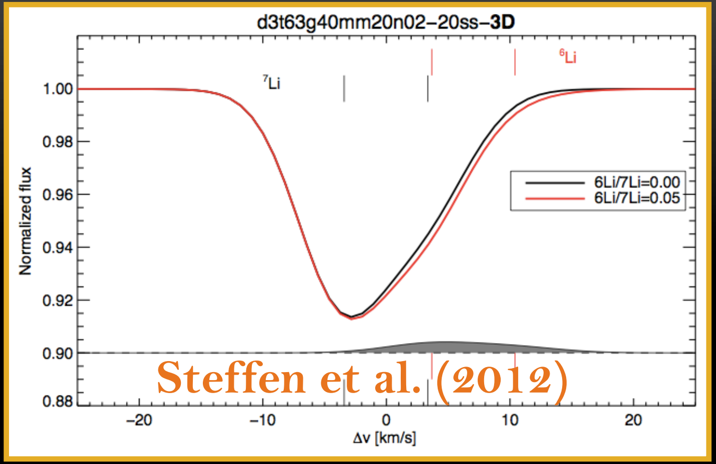
- $A(^7\text{Li}) = 2.75 \pm 0.02$
- $^6\text{Li}/^7\text{Li} \approx 10^{-4}$

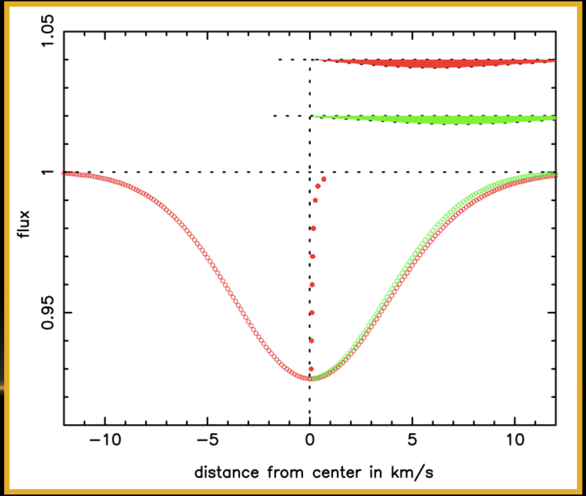
Pitrou et al. (2018)

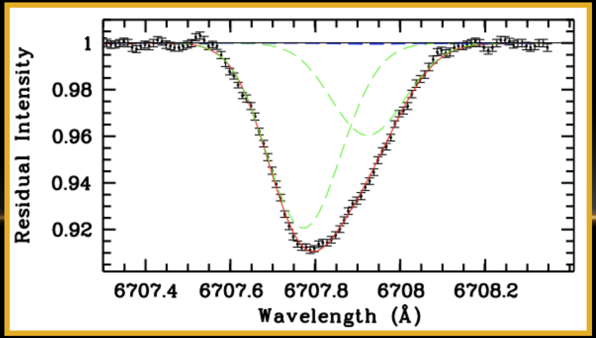
Asplund et al. (2006)

^{6}Li Measurement ?

- ^{6}Li/^{7}Li is measured from the asymmentry in the red wing of the Li 6708A doublet
- ^{6}Li/^{7}Li in metal-poor stars needs 3D-NLTE modeling using 3D hydrodynamical model atmospheres



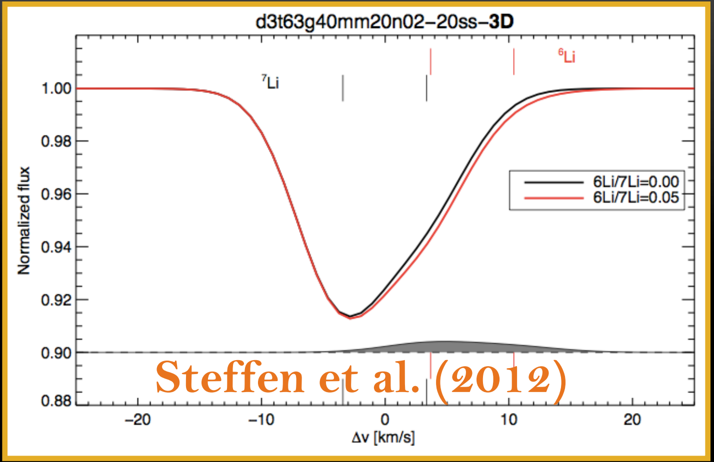


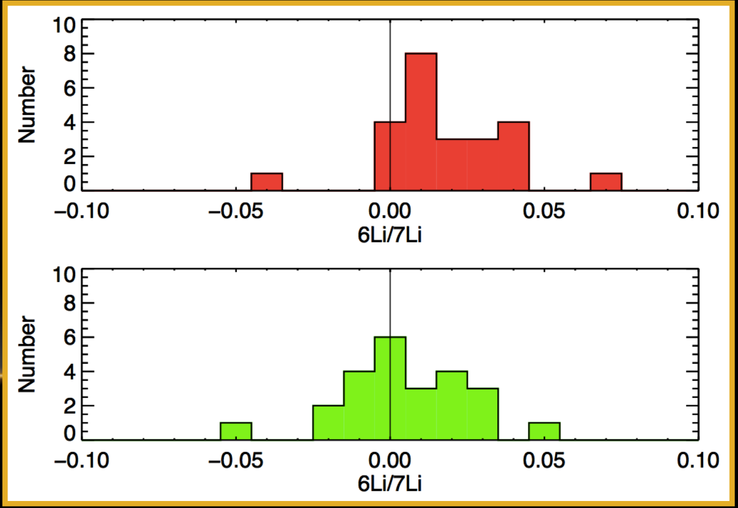


Cayrel et al.
(2007, A&A Letters)

^{6}Li Measurement ?

- ^{6}Li/^{7}Li is measured from the asymmentry in the red wing of the Li 6708A doublet
- ^{6}Li/^{7}Li in metal-poor stars needs 3D-NLTE modeling using 3D hydrodynamical model atmospheres
- Using 3D-NLTE, most of the stars show no ^{6}Li Cayrel et al. (2007); Steffen et al. (2012); Lind et al. (2013); González Hernández et al. (2019); Wang et al. (2022)

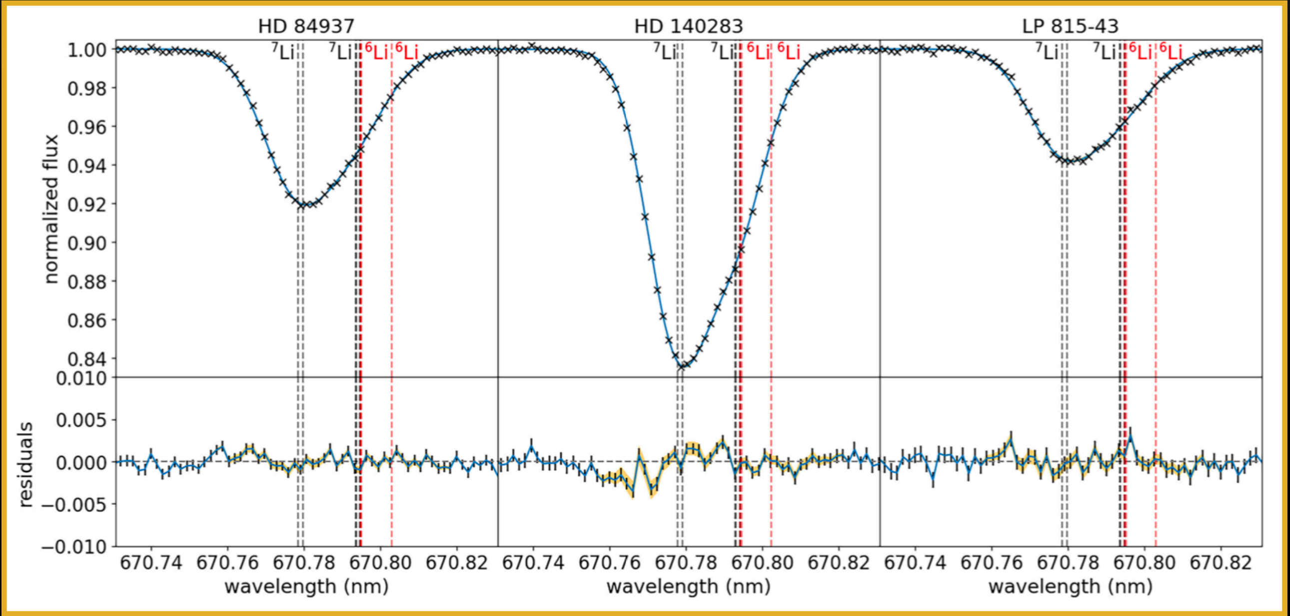




Cayrel et al.

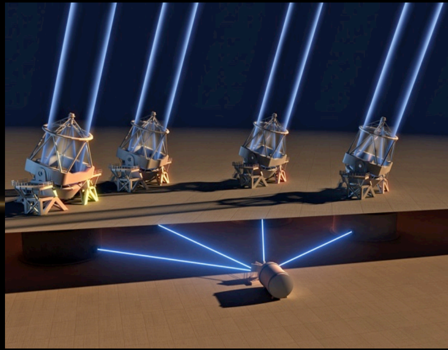
(2007, A&A Letters)

OBSERVATIONS: ESPRESSO



- ESPRESSO observations
  - R~146,000 (LiI6708)
  - S/N > 1000 /pixel
  - 0.5 km/s /pixel
- 6Li/7Li ~ 0.0 %

[Fe/H] = -2.05 [Fe/H] = -2.29 [Fe/H] = -2.68



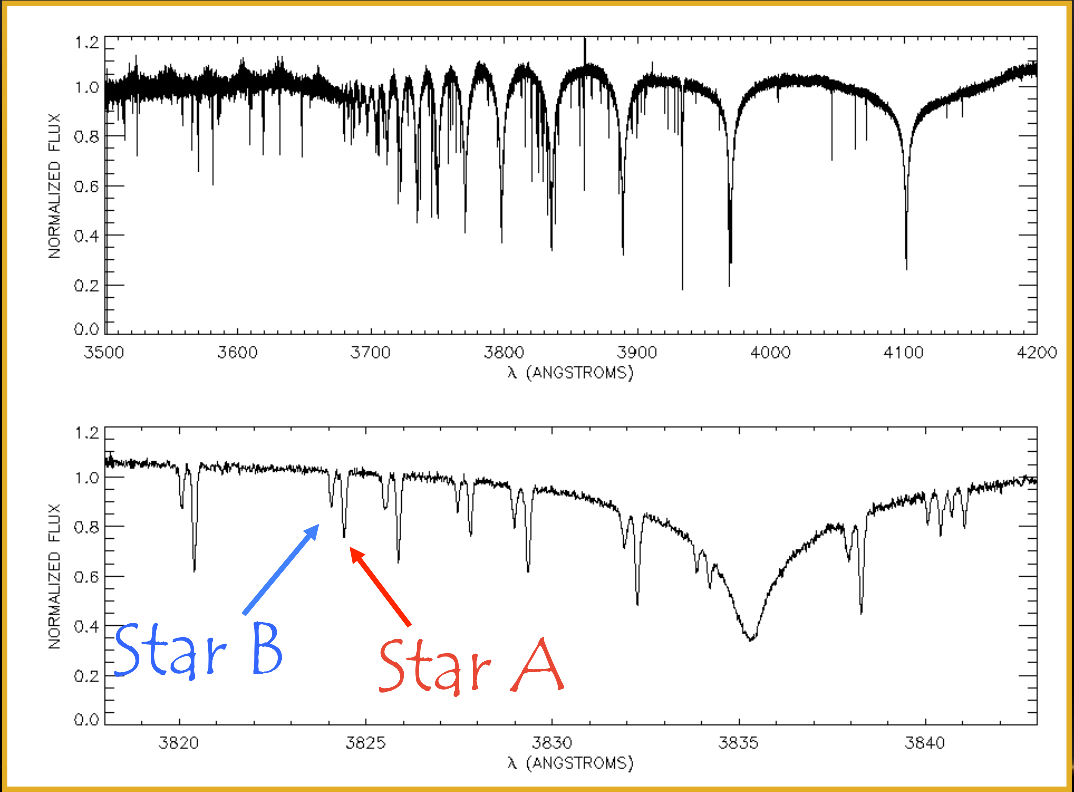
Wang et al. (2022, MNRAS)

OBSERVATIONS: CS 22876-032

- Spectroscopy with VLT/UVES with IS#3
- Spectral region 500-680 nm
- $\lambda/d\lambda$ ~110,000
- 28 useful spectra of ~3000 s taken during 4 visitor nights at VLT in 2007

González Hernández et al. (2019, A&A)

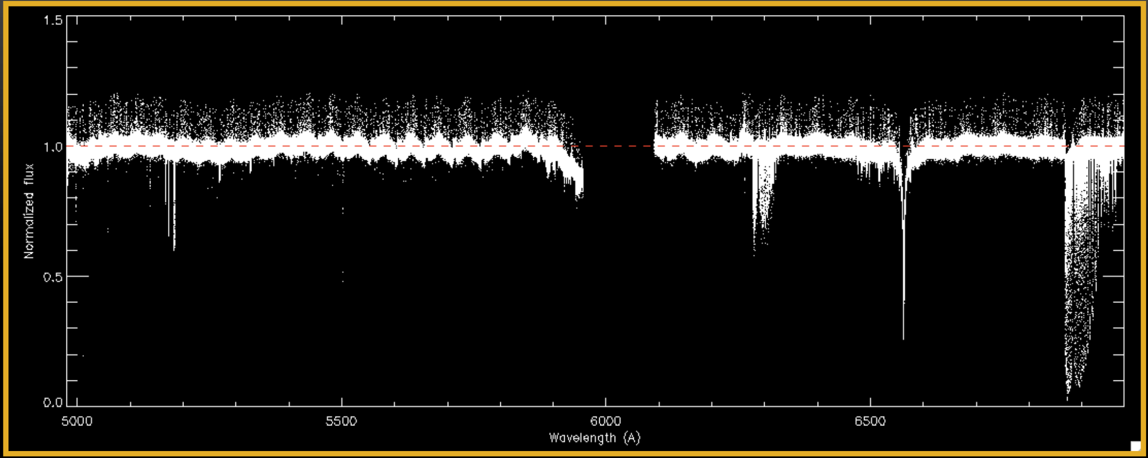
Observations: CS 22876-032

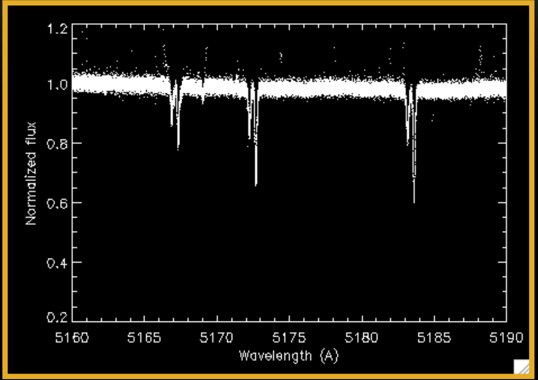


- UVES/VLT spectrum shows [Fe/H]~ -3.7
- about 1 dex less metallicity that the next EMP with an attempt to measure ^{6}Li/^{7}Li

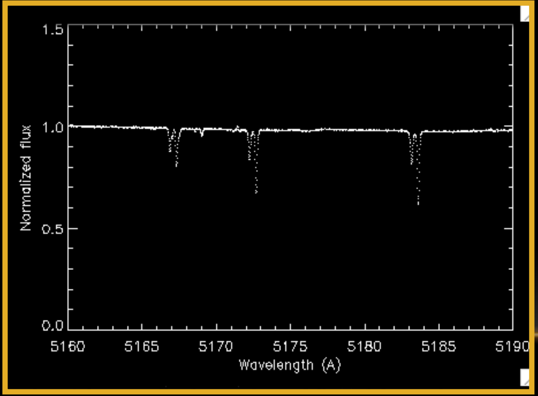
González Hernández et al. (2008, A&A; 2019, A&A)

Observations

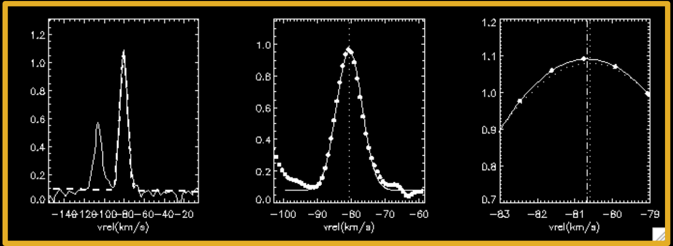




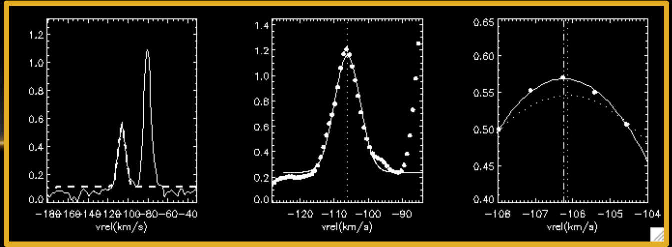
Mg Ib triplet



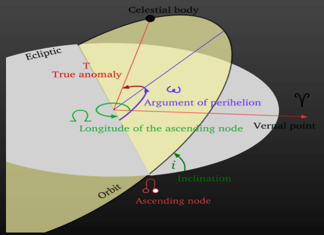
CCF Star A

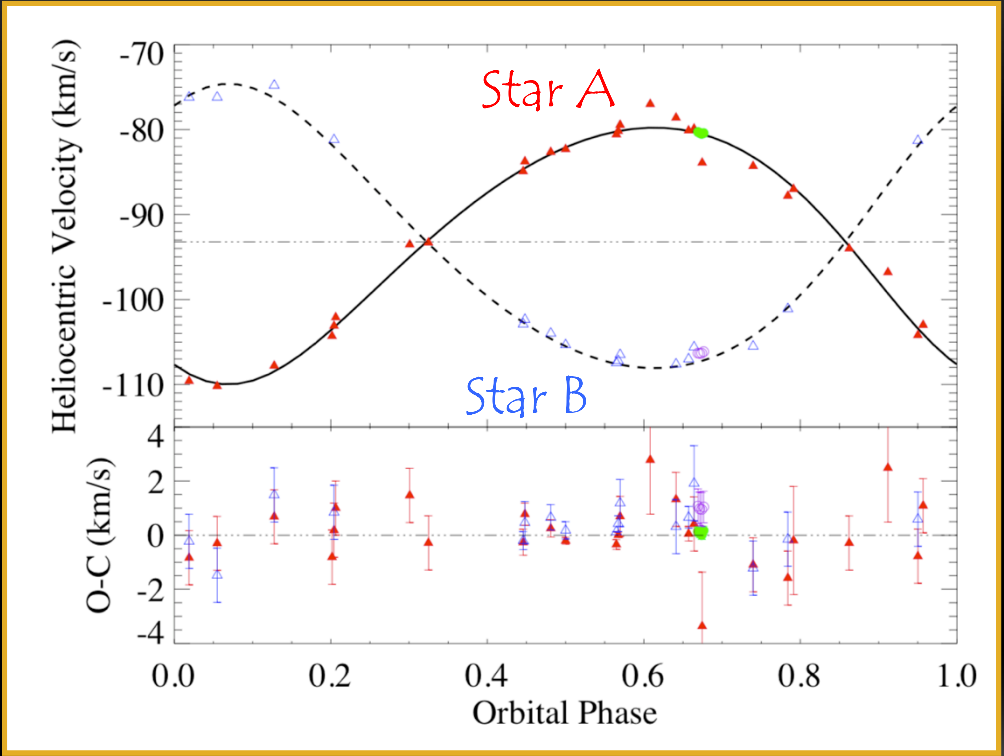


CCF Star B



ORBITAL ELEMENTS





New UVES_IS#3@VLT data

+

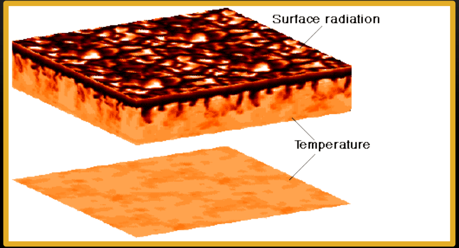
Norris et al. (2000)

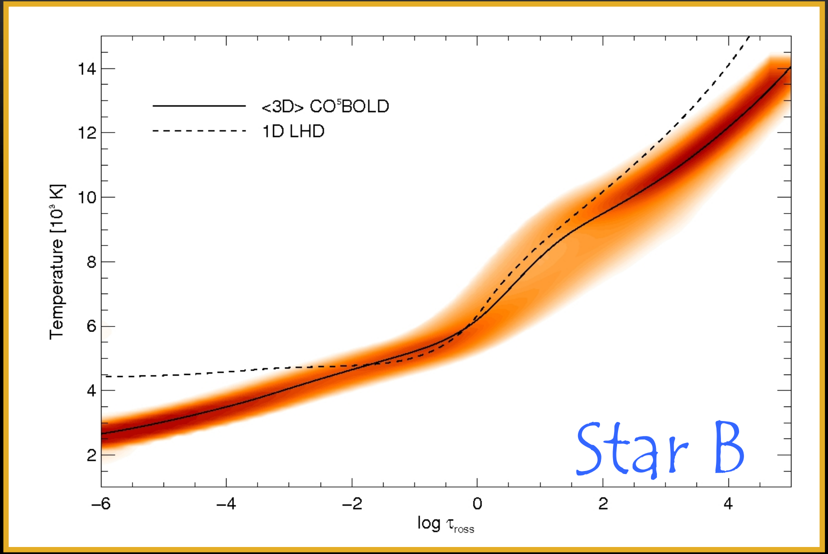
González Hernández et al. (2008, A&A)

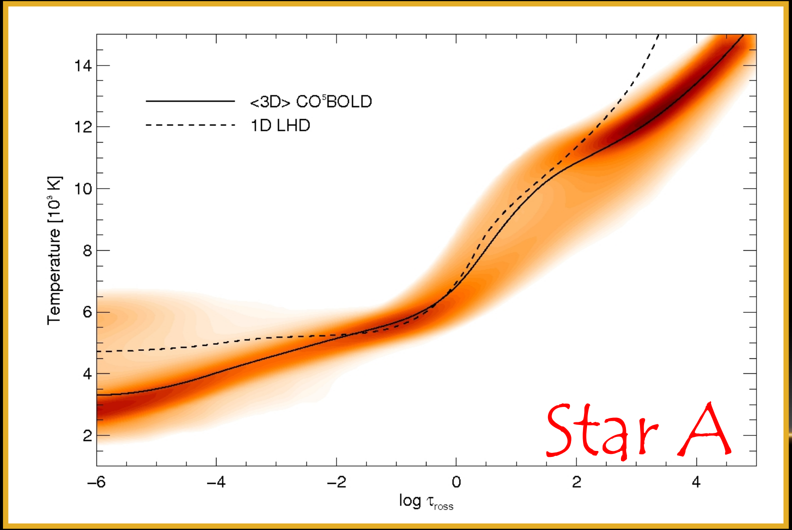
Mass ratio ~ 0.91

González Hernández et al. (2019, A&A)

3D Model Atmospheres

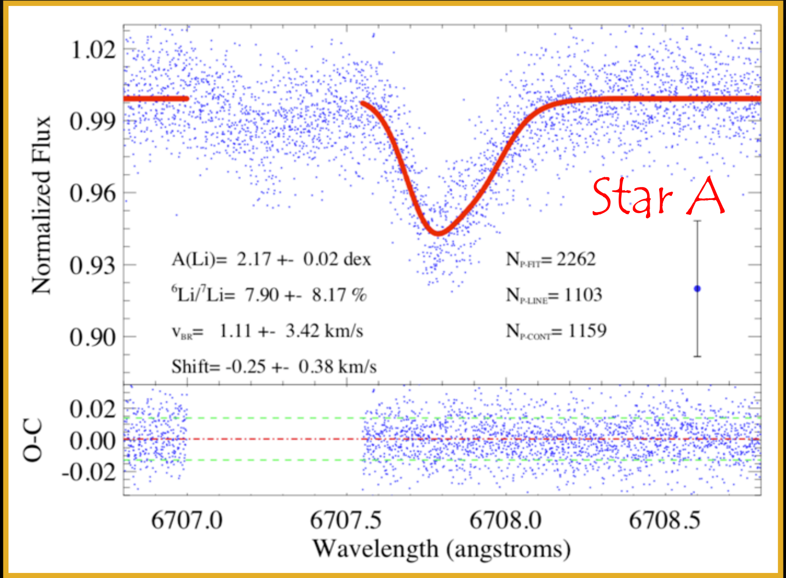






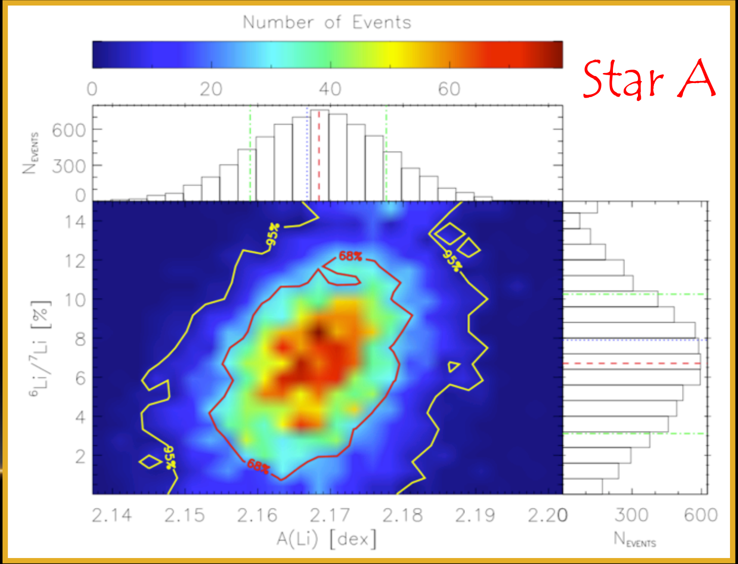
Ludwig et al. (2009)

^{6}Li/^{7}Li : CS 22876-032



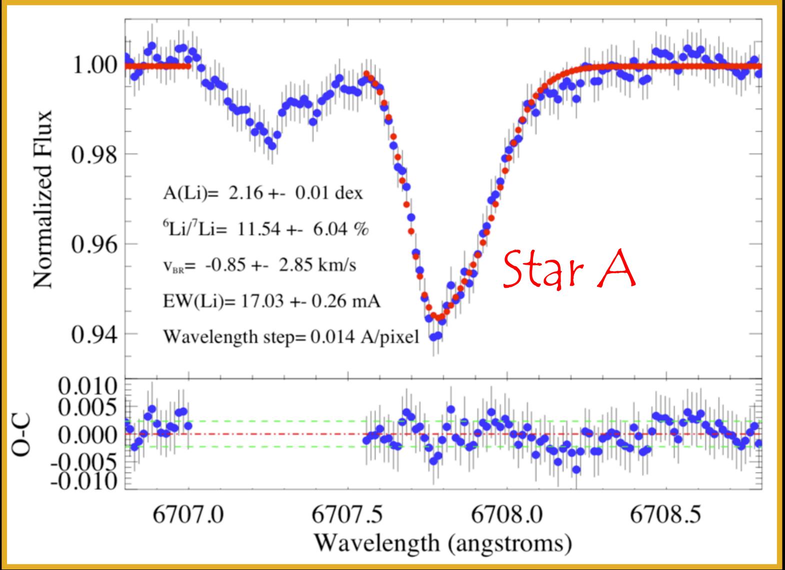
^{6}Li/^{7}Li = 7.9 ± 8.2 %

A(Li) = 2.17 ± 0.02 dex



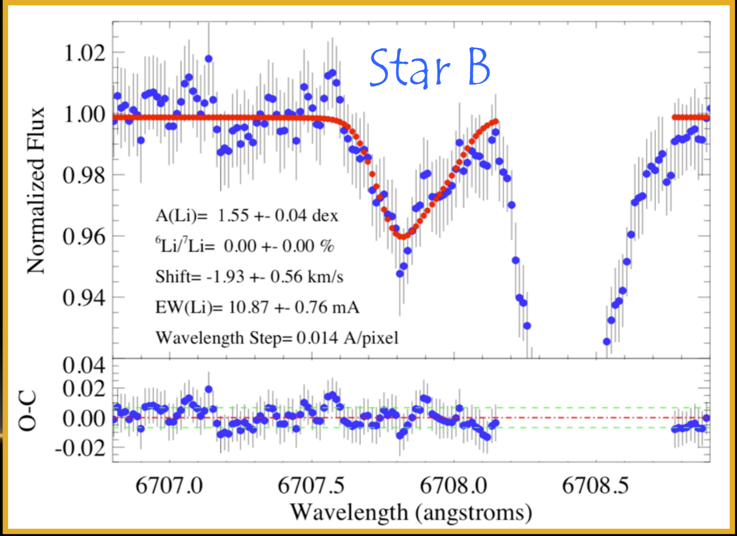
González Hernández et al. (2019, A&A)

Li : CS 22876-032



$A(Li)_{StarA} = 2.16 \pm 0.01$ dex

$A(Li)_{StarB} = 1.55 \pm 0.04$ dex



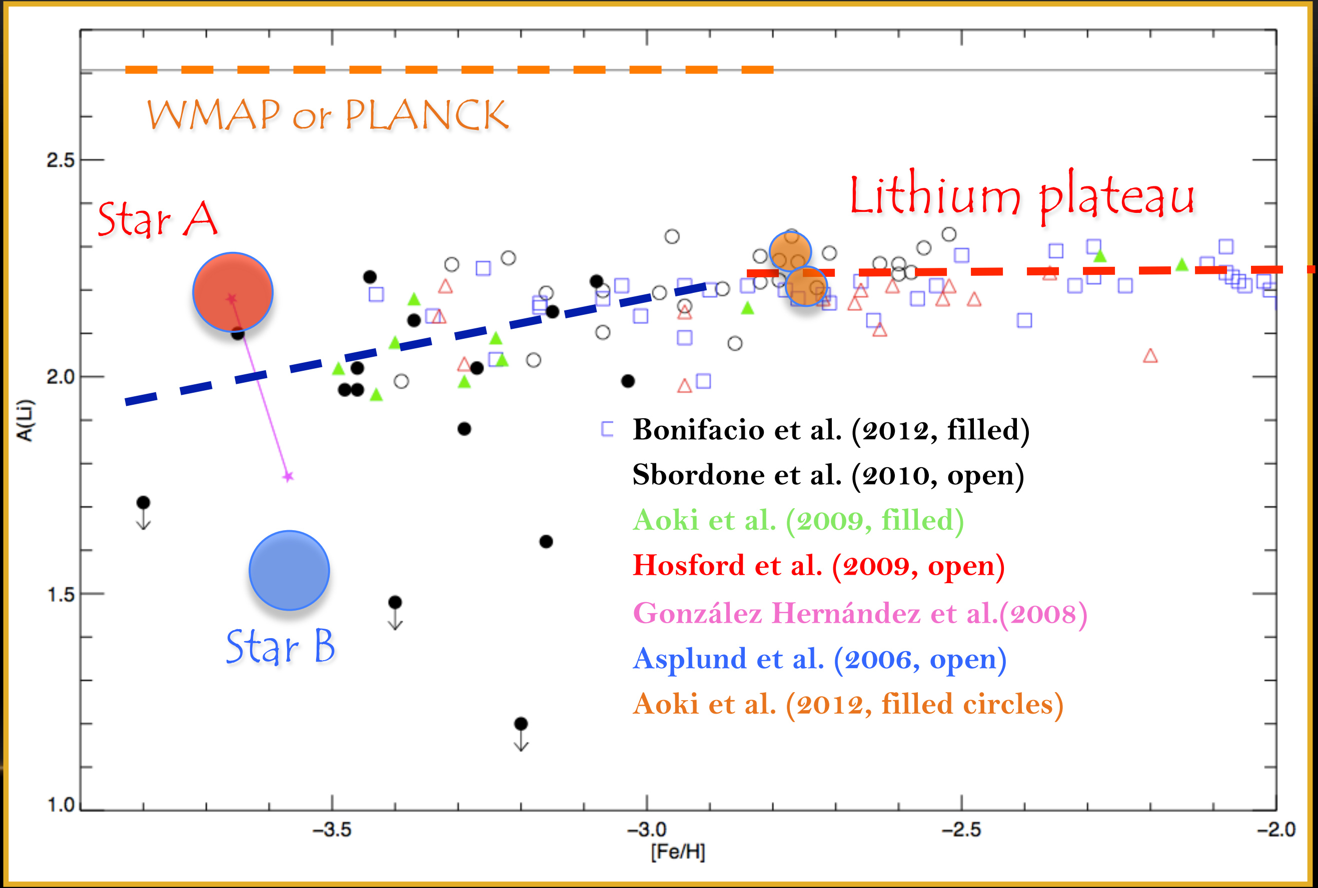
González Hernández et al. (2019, A&A)

Lithium in Metal Poor Stars

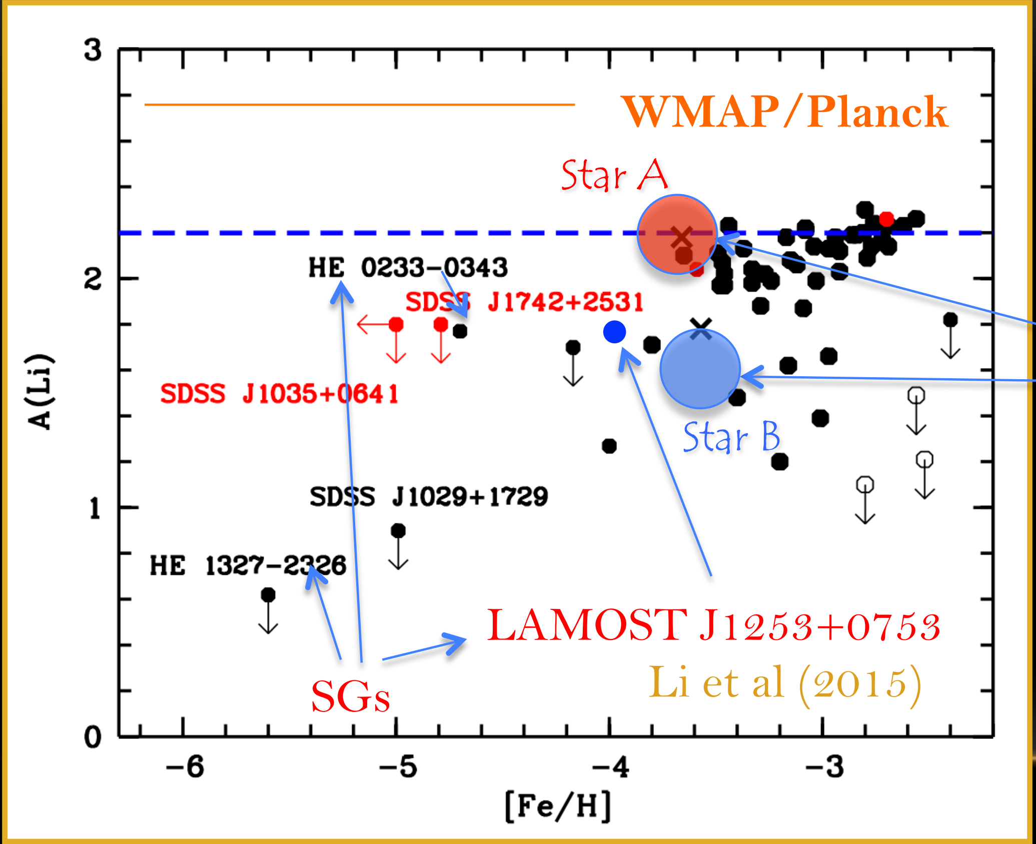
WMAP or PLANCK :
(A(Li)~2.71 ± 0.04
Coc & Vangioni 2017)

-3.8 < [Fe/H] < -2.0

Sbordone et al.
(2012, MSAI)



Lithium in Unevolved Extremely Iron Poor Stars



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

CS 22876 -032 AB

González Hernández et al. (2008, A&; 2019, A&A)

Bonifacio et al. (2015)

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)
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)

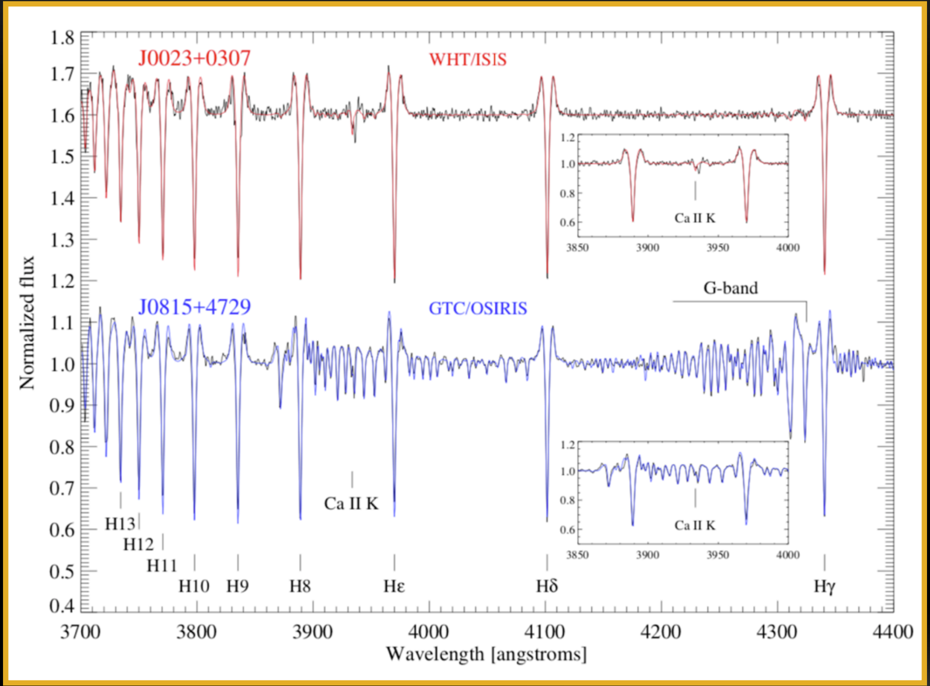
14 stars at [Fe/H] < - 4.5 (known in 2019)

2 < logg < 3

3 < logg < 4

logg > 4

Extremely Iron Poor Stars: J0815 & J0023



J0023+0307: ISIS spectrum

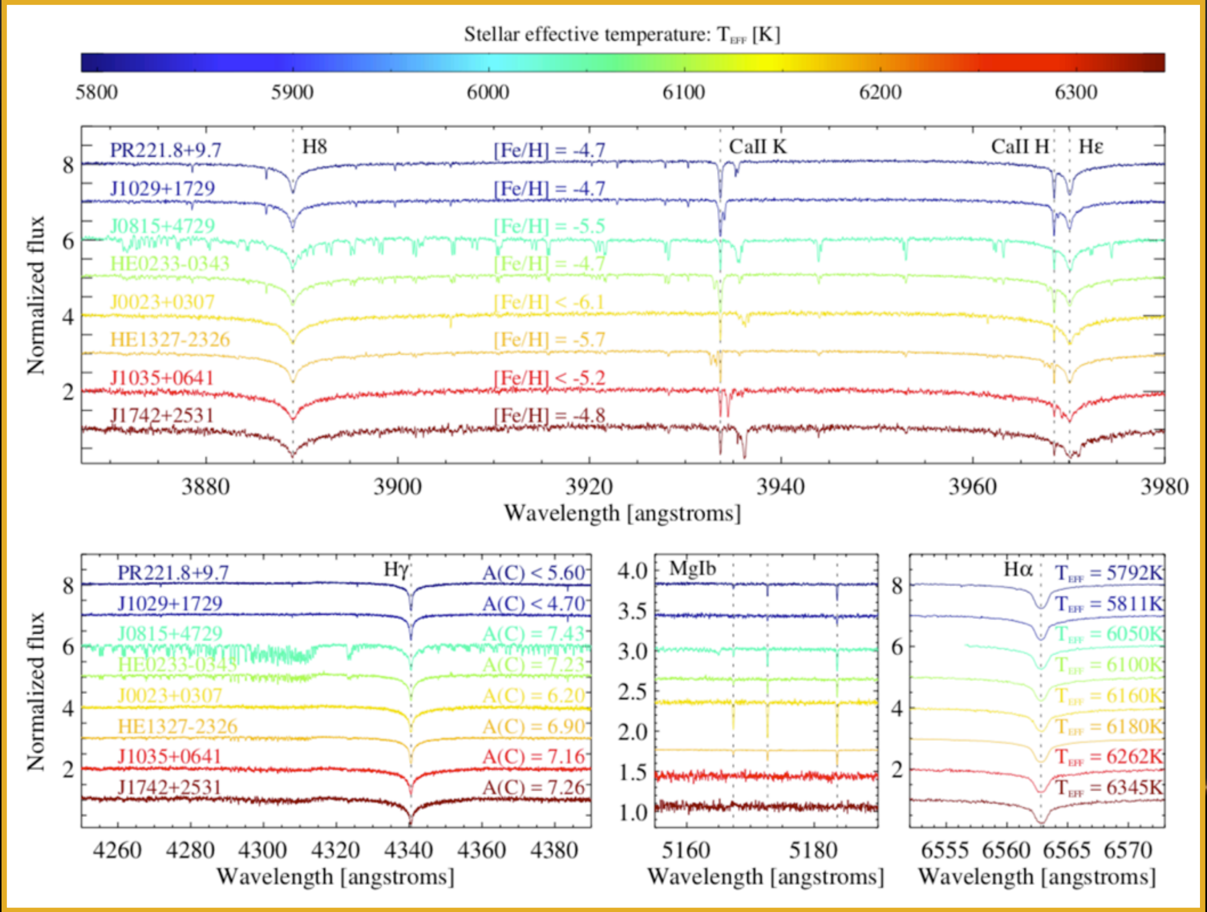
Aguado et al.
(2018a, ApJ Letters)

J0815+4729: OSIRIS spectrum

Aguado et al.
(2018b, ApJ Letters)

González Hernández et al. (2023, MSAI)

Extremely Iron Poor Stars: J0815, J0023 vs UMPs



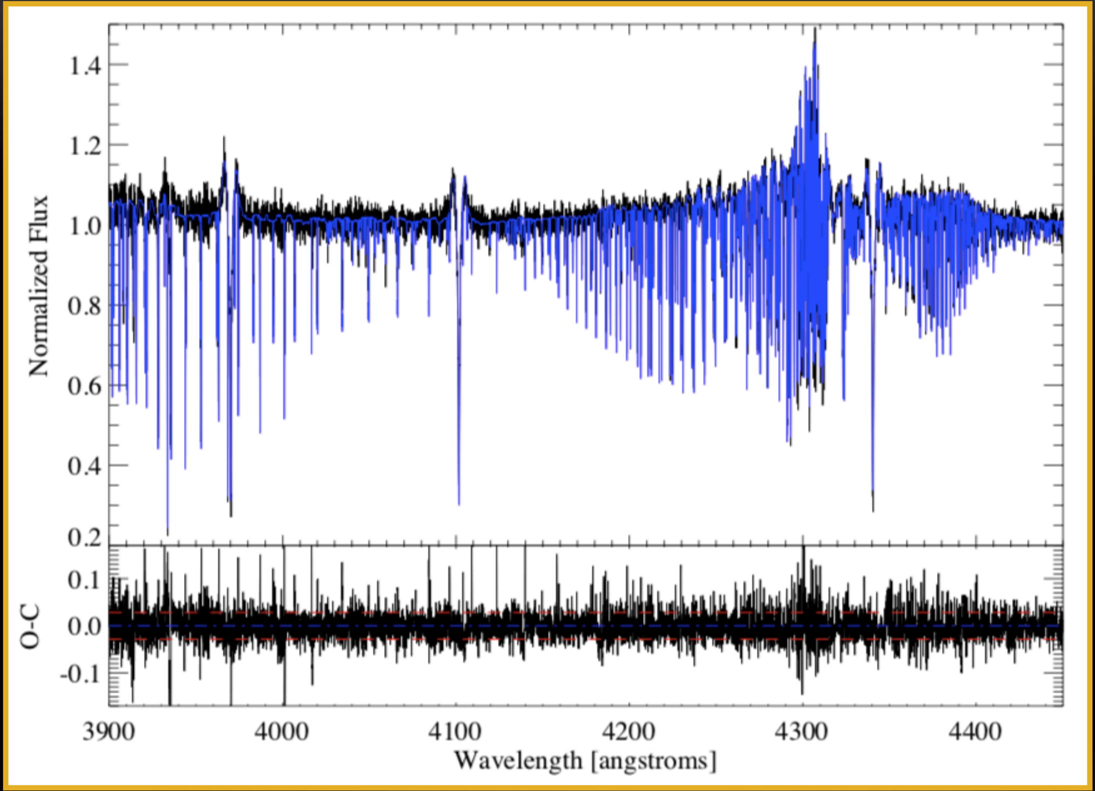
Updated improved spectrum of PR221 from

Lardo et al. (2021, MNRAS)

González Hernández et al. (2020, ApJ Letters)

González Hernández et al. (2023, MSAI)

EXTREMELY IRON POOR STARS: J0815 - CARBON



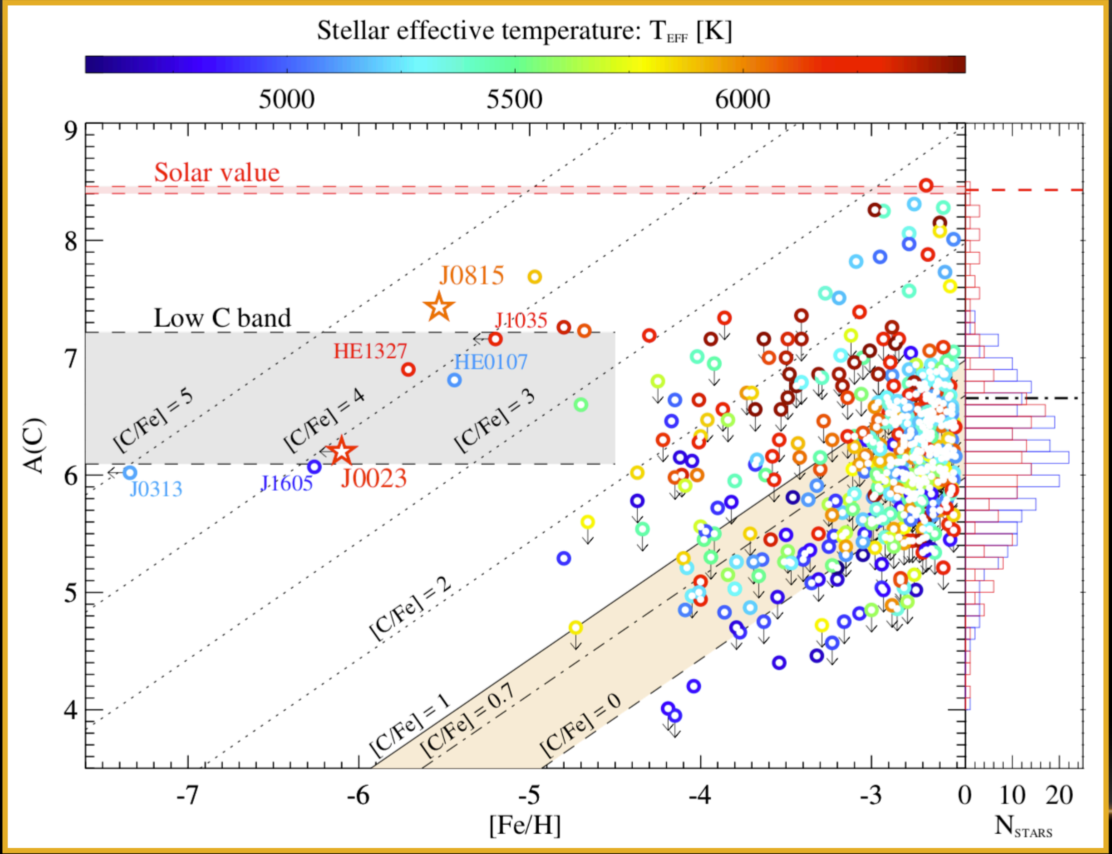
$A(C) = 7.43 \pm 0.17$

$[C/Fe] = 4.49 \pm 0.11$

González Hernández et al. (2020, ApJ Letters)

Image credit: Gabriel Pérez (IAC)

Carbon in Metal Poor Stars



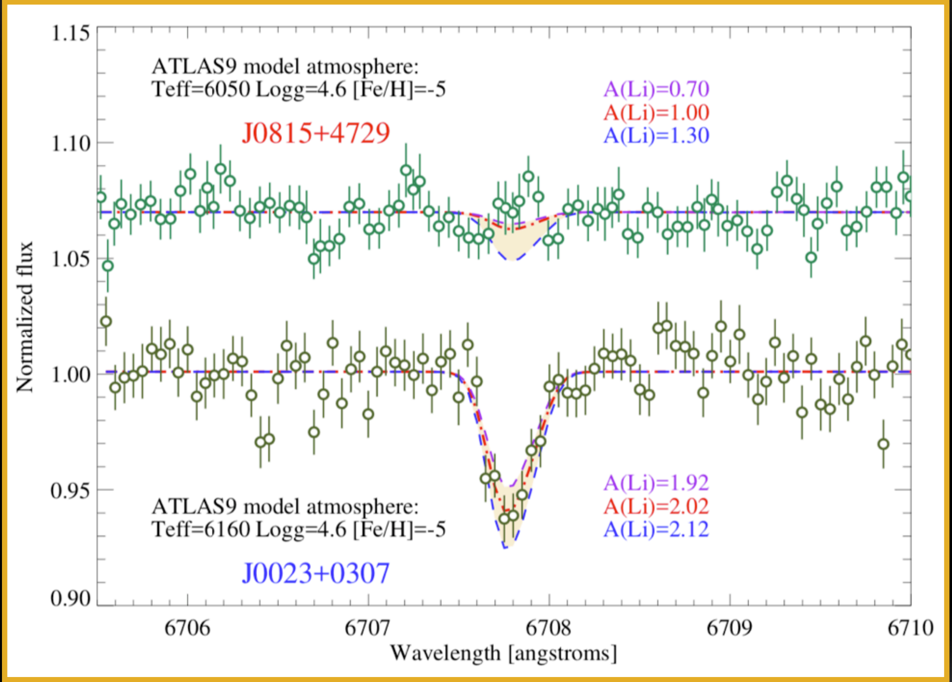
González Hernández et al. (2023, MSAI)

[Fe/H] < -2.5

J0815:
A(C) = 7.43
J0023:
A(C) = 6.20

Including Pristine stars
Aguado et al. (2019b, MNRAS)

Extremely Iron Poor Stars: Li features



J0815+4729: HIRES SPECTRUM

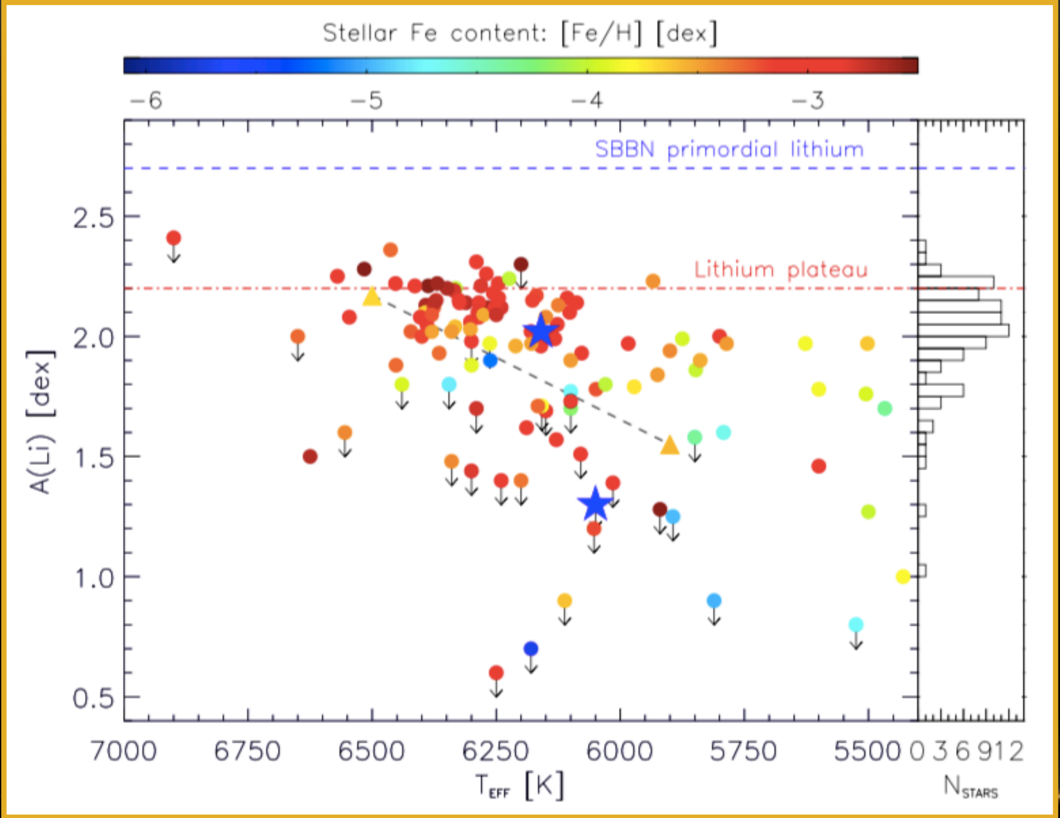
González Hernández et al. (2020, ApJ Letters)

J0023+0307: UVES SPECTRUM

Aguado et al. (2019, ApJ Letters)

González Hernández et al. (2023, MSAI)

LITHIUM IN METAL POOR STARS

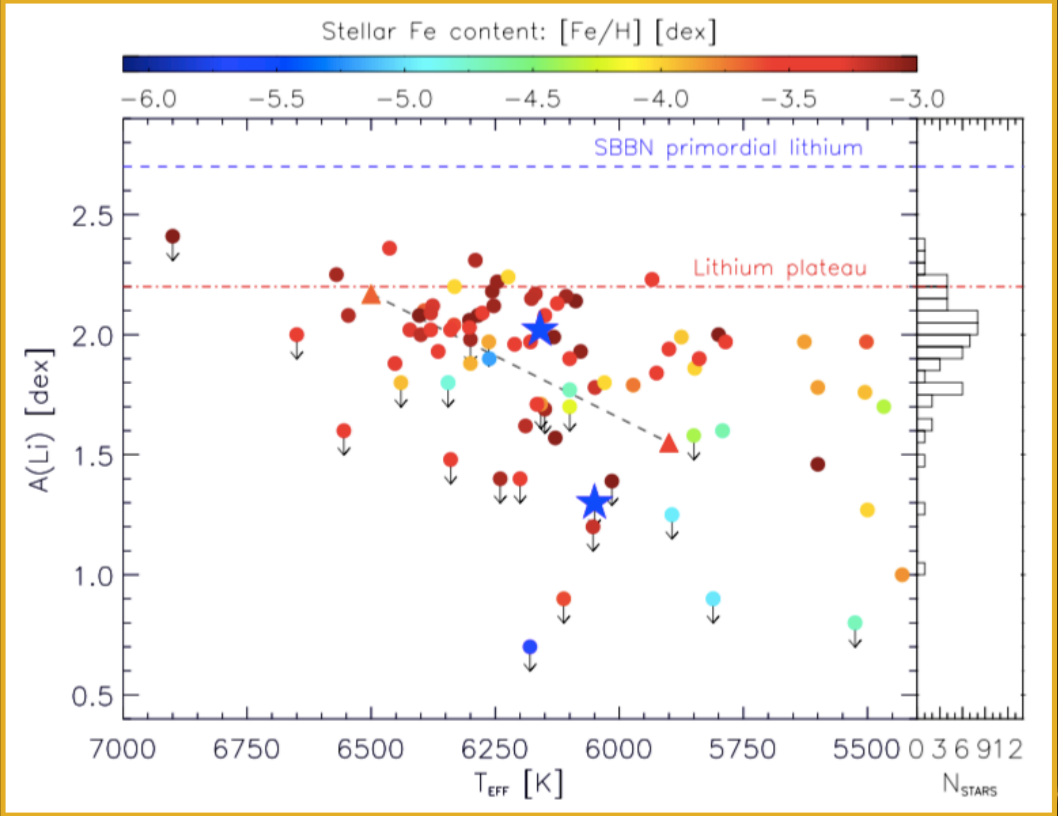


-6.2 < [Fe/H] < -2.5

No clear trend in Teff

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

Lithium in Metal Poor Stars



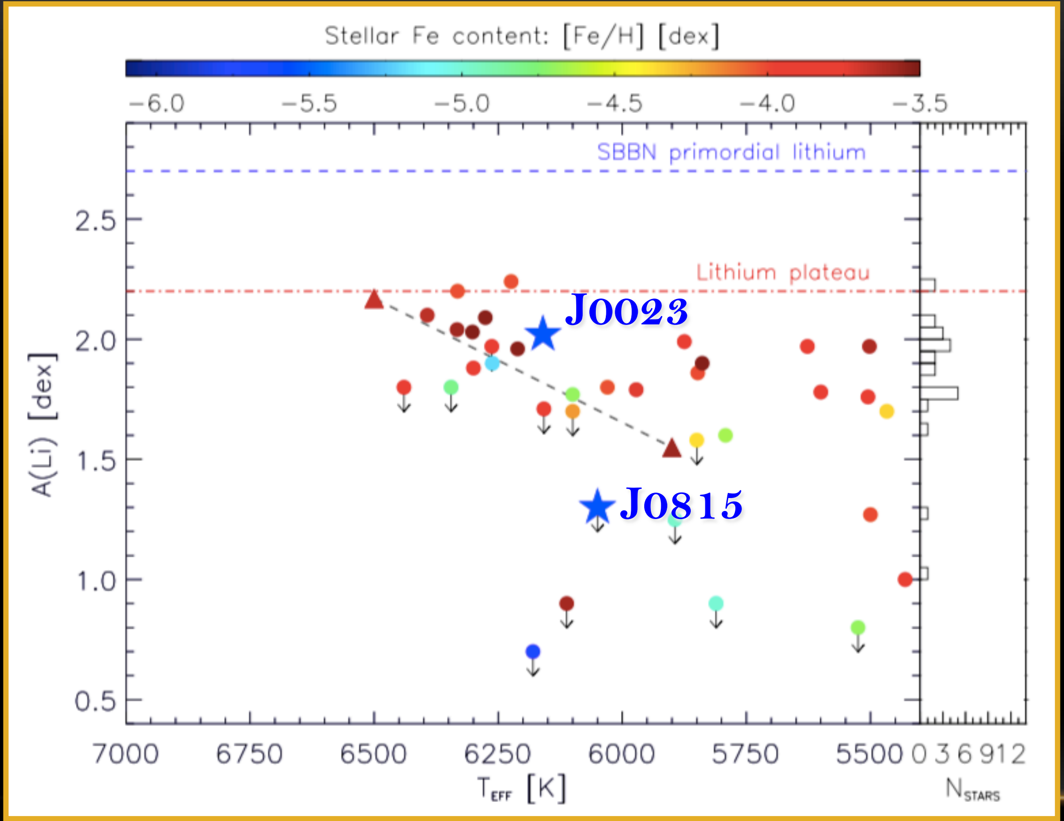
-6.2 < [Fe/H] < -3.0

No clear trend in Teff

Mean Li abundance decreases with [Fe/H]

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

Lithium in Metal Poor Stars



$-6.2 < [Fe/H] < -3.5$

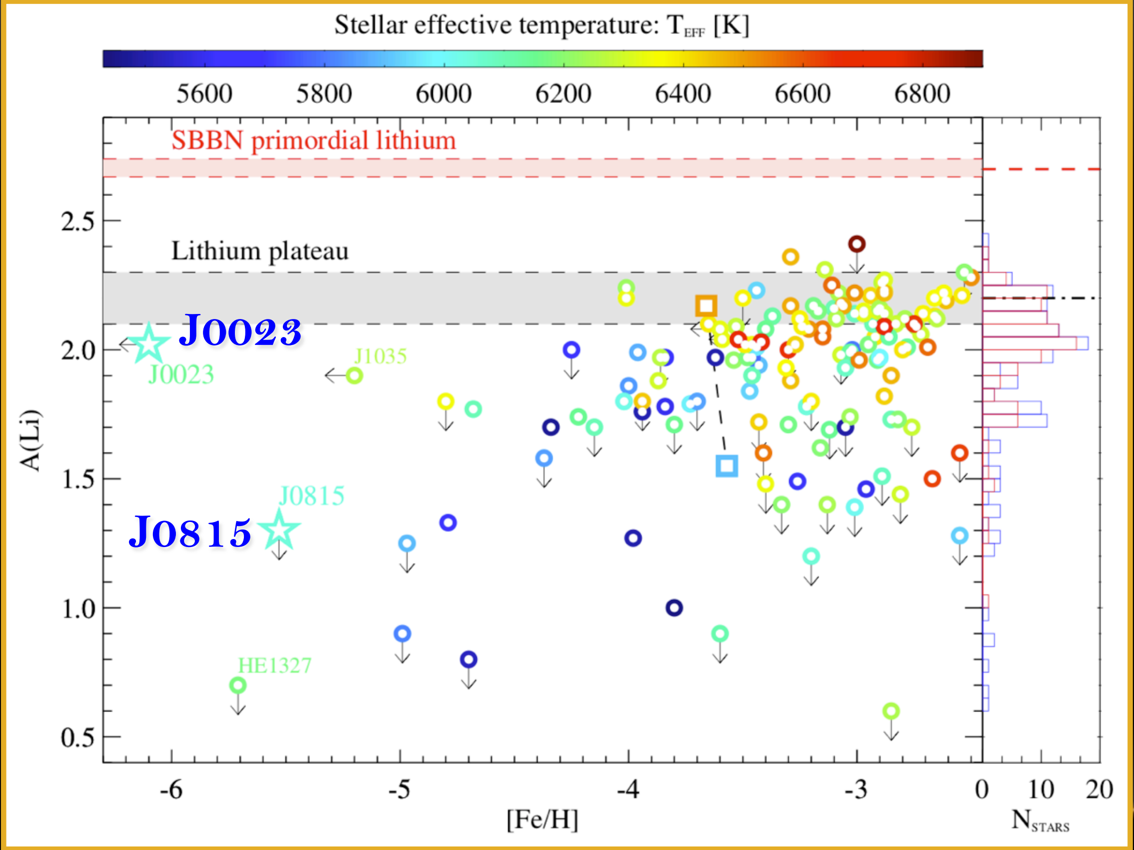
No clear trend in Teff

Mean Li abundance decreases as [Fe/H] decreases

Scatter increases as [Fe/H] decreases

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

Lithium in Metal Poor Stars



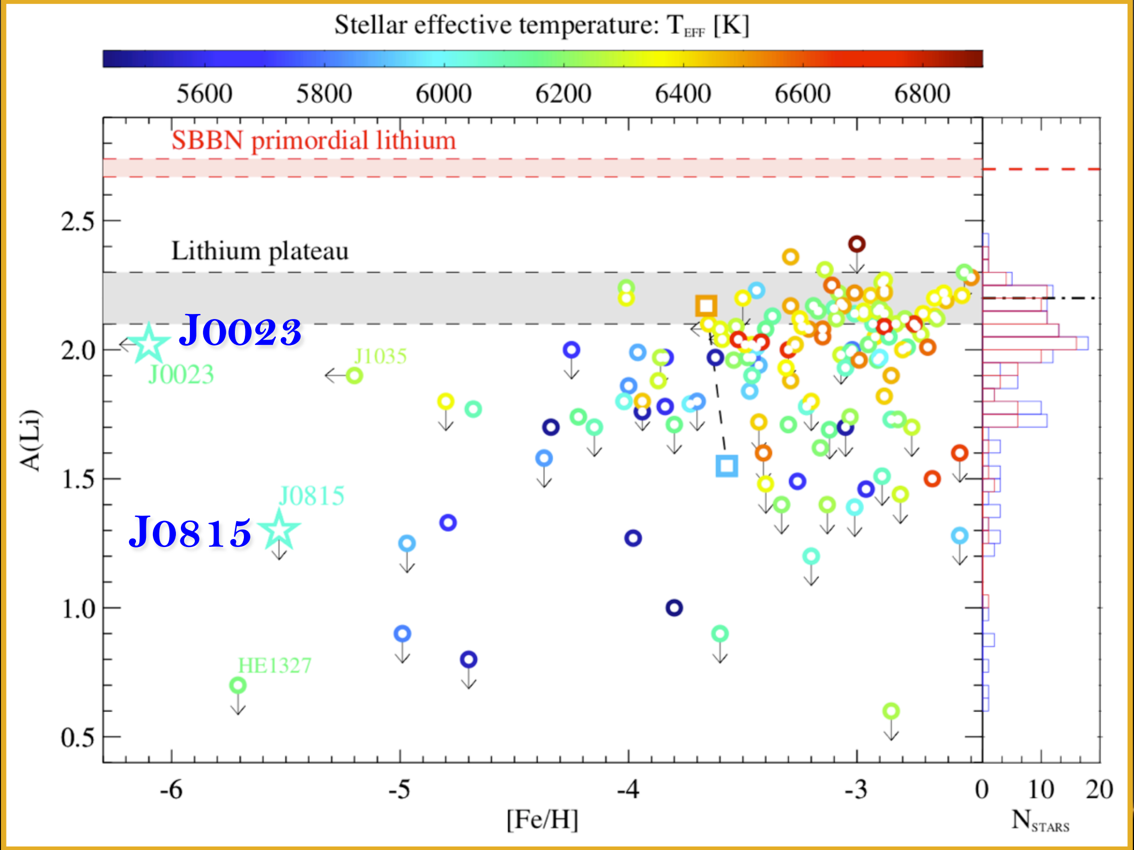
González Hernández et al. (2023, MSAI)

$-6.2 < [Fe/H] < -2.5$

J0023:
A(Li) = 2.02 ± 0.08
J0815:
A(Li) < 1.30

Including Pristine stars :
Kielty et al. (2021, MNRAS);
Lardo et al. (2021, MNRAS)

Lithium in Metal Poor Stars



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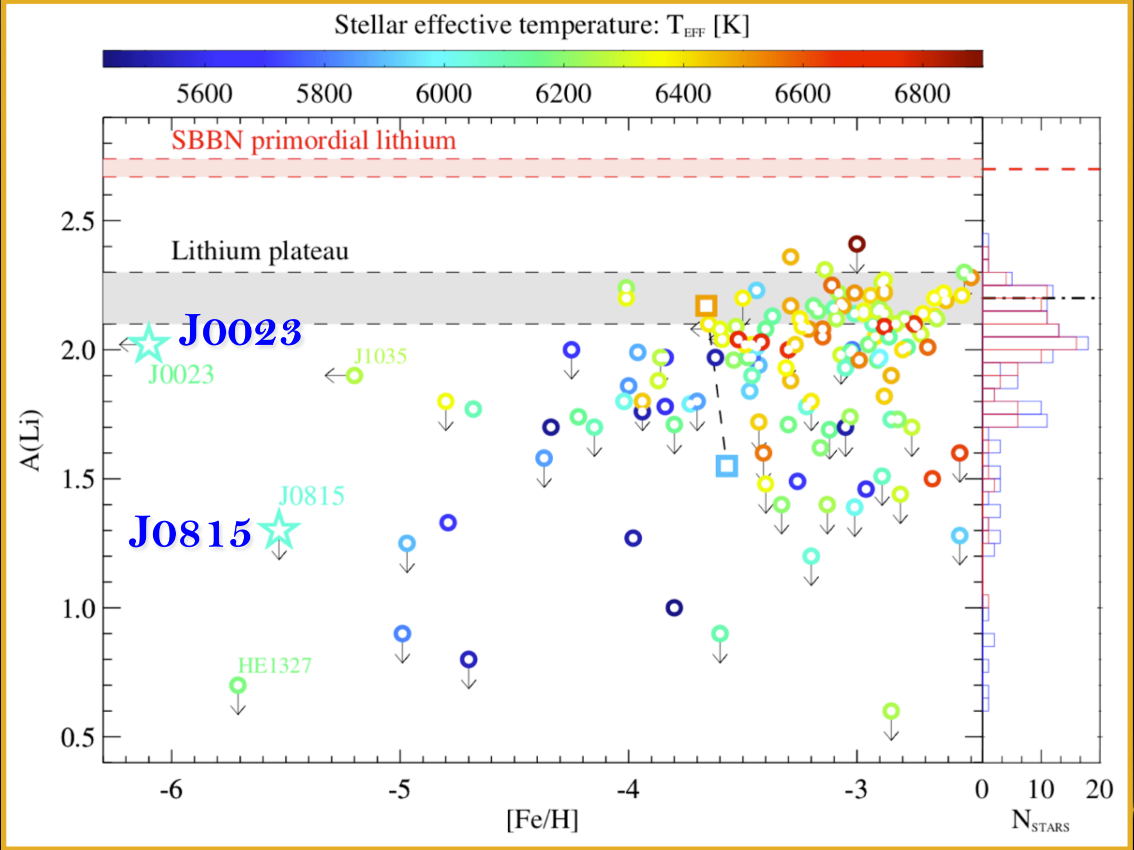
Meltdown A(Li) vs [Fe/H]

Scatter increases as [Fe/H] decreases

Lithium in Metal Poor Stars



González Hernández et al. (2023, MSAI)

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J0023:

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J0815:

A(Li) < 1.30

But we found J0023 !! with A(Li) ~ Li plateau

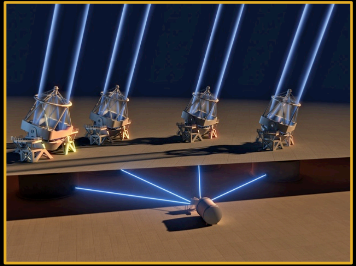
Upper-envelope of A(Li) in -6.2 < [Fe/H] < -2.5

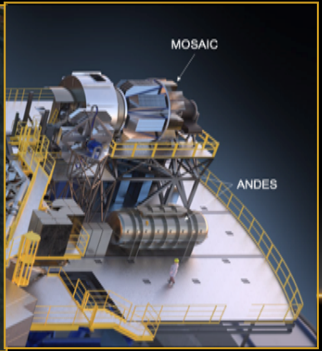
Still surprising not finding stars between observed Li upper-envelope and the SBBN primordial A(Li)

Future

- Searching for iron-poor stars:
  - Gaia DR3, PRISTINE-WEAVE@WHT, DESI, …
- Detailed chemical composition :
  - HORuS@GTC, HIRES@KeckI, HDS@Subaru, UVES@VLT, ESPRESSO@VLT (Multi-UT),…
  - CHORUS@GTC, ANDES@ELT, TMT, GMT,…






CHORUS @ 10.4m-GTC

- Ultra-stable spectrograph for the GTC
  - UVS spectrograph (R~25k – 0.31 – 0.42 µm)
  - VIS spectrograph (R~100k – 0.42 – 0.78 µm)
  - Science cases:
    - Earth-like planets in the HZ of nearby star
    - Fundamental constants
    - Chemical evolution in the MW, and nearby Galaxies

P.I. : Jifeng Liu

First light 2028?

Credit: Pablo Bonet / IAC

Zhang et al. (2020, SPIE)

EXCELENCIA SEVERO OCHOA

Lithium in the most Iron-Poor Unevolved Stars Known and the Cosmological Lithium Problem

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GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN

Nuclei in the Cosmos (NIC XVII)

Institute for Basic Science (IBS), Daejeon, Korea

17–22 September 2023

NGC 6397: SG vs. MS

- Li surface abundance changes with evolutionary status.
- The Li abundance pattern seen in the globular cluster NGC 6397 has not been observed so far in field stars.
- The cosmological lithium problem still awaits a solution
- Our observations call for new investigations into the stellar physics, including gravity waves, atomic diffusion, winds and turbulent mixing

González Hernández et al. (2009, A&A Letters)