Lithium Abundances
in
Extremely Metal-Poor stars

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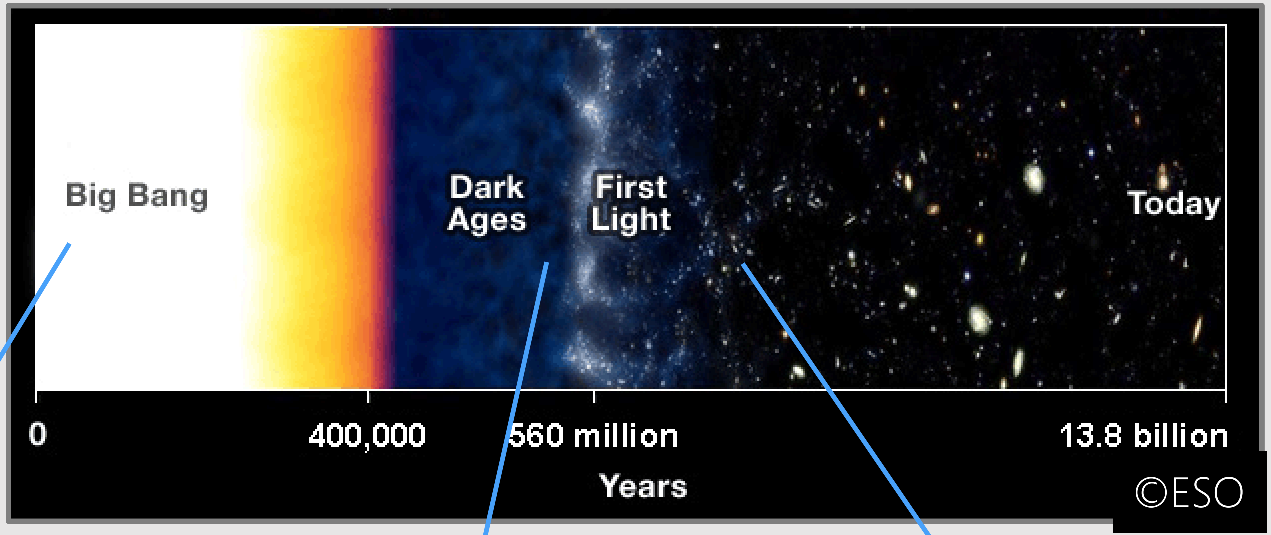
in collaboration with W. Aoki et al.
Matsuno et al. (2017a, PASJ; 2018b, AJ)

Formation of metal-poor stars



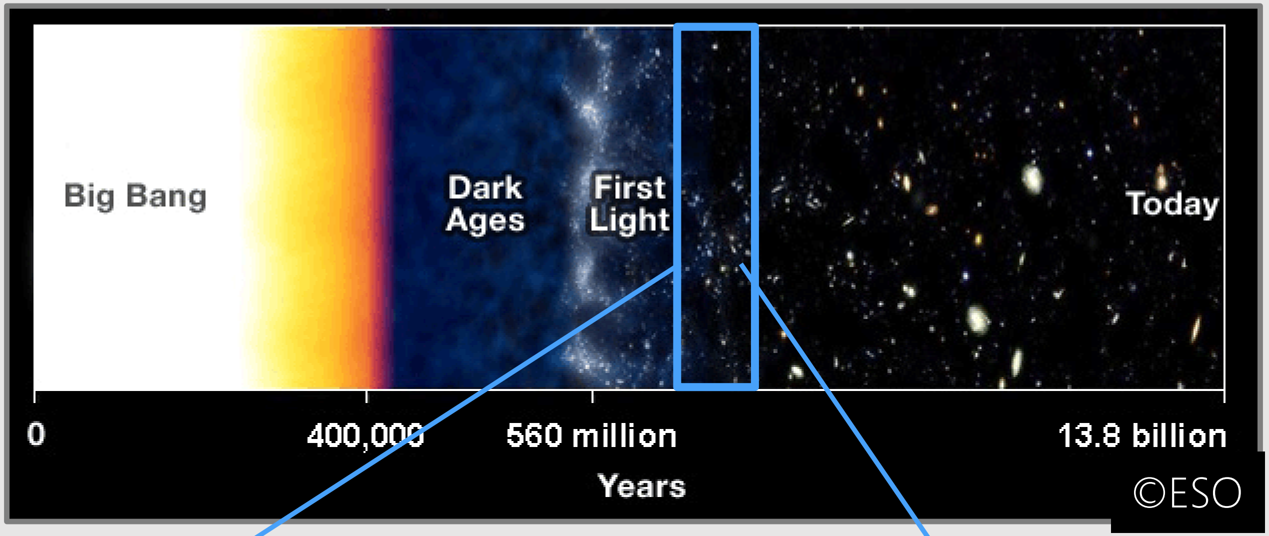
Big Bang → **First Stars** (z~20) → **Second generation**

- D, ^{3}He, ^{4}He, ^{7}Li
- CMB radiation

- Massive
- First metal enrichment

- Can be low mass (e.g., $<0.8\ M_{sun}$)

Information from metal-poor stars



- Chemical composition of ISM reflects nucleosyntheses by Big Bang and by first stars
- Star hardly changes its surface abundance during the evolution

Second generation

- Can be low mass (e.g., $<0.8\ M_{sun}$)

Metal poor star at z=0

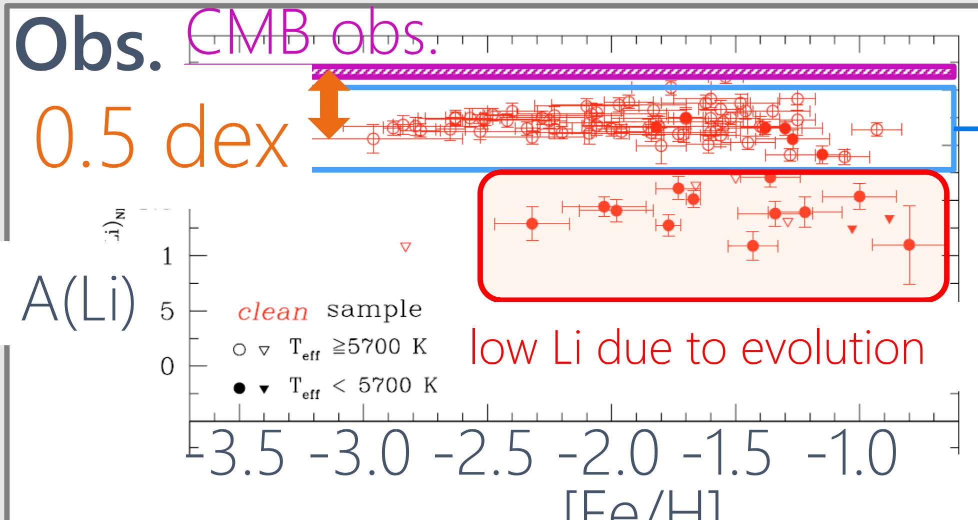
➡ **BBN** (This talk)

First stars

(e.g., Ishigaki et al. 2014; 2018)

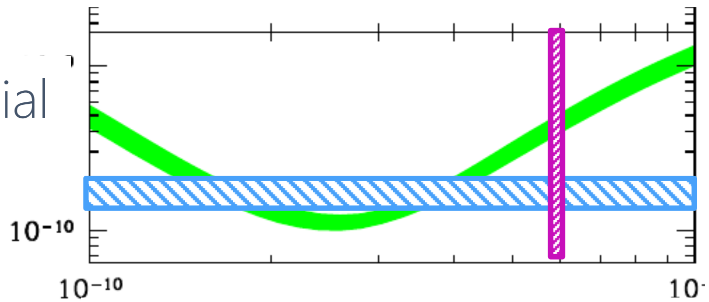
From Metal-Poor Stars to Big Bang

Obs.



Charbonnel+05

BBN models



Cyburt+16

def.

$A(X) = \log N_X/N_H + 12$

$[X/Y] = \log N_X/N_H - \log(N_X/N_H)_\odot$

Spite plateau

almost constant→primordial

?

Constraints on Baryon density

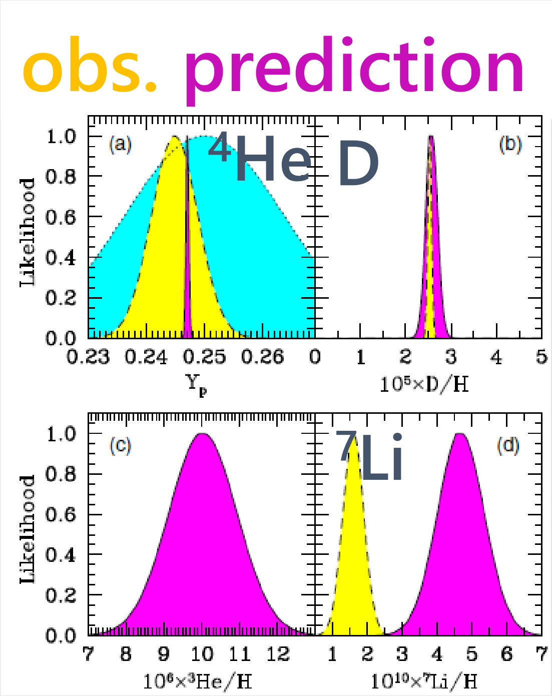
CMB observation

WMAP(2001-10),Planck (2009-13)

Is the standard BBN model wrong?

- **Uncertain reaction rates**

  precise enough



Cyburt+16

Is the standard BBN model wrong?

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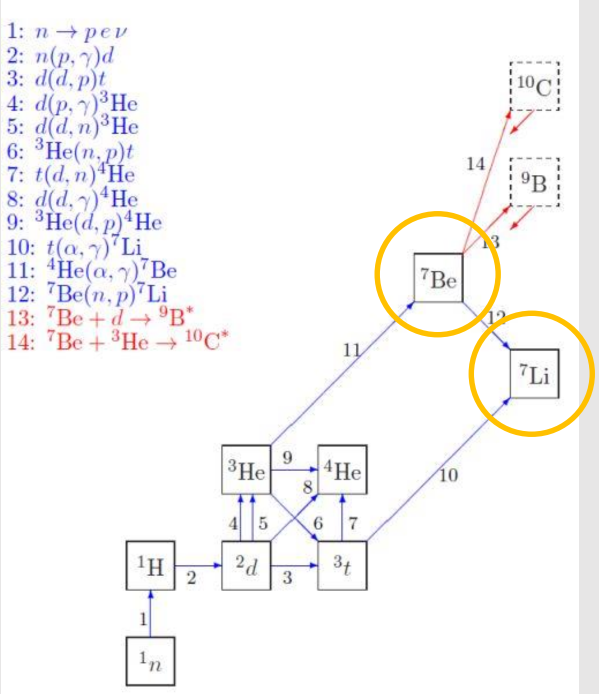
  precise enough

- **Unknown channel** (Chakraborty et al., 2011)

  mostly ruled out by experiments

  (e.g., Kirsebom & Davids, 2011; O'Malley et al., 2011)



Fields+11

Is the standard BBN model wrong?

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  precise enough

- **Unknown channel** (Chakraborty et al., 2011)

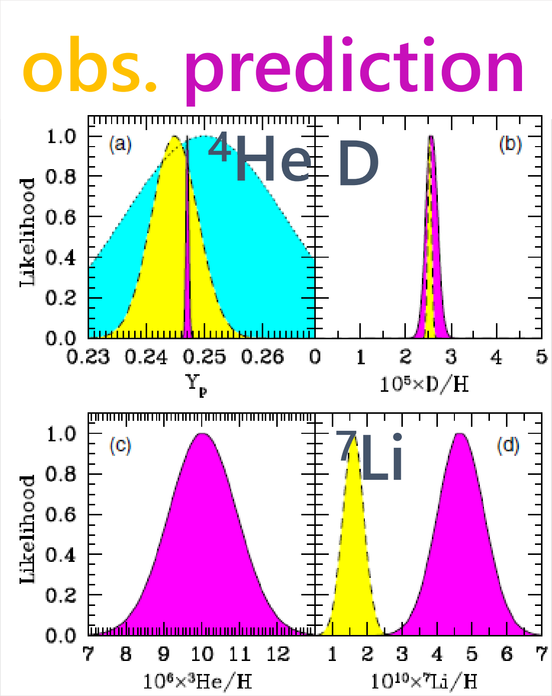
  mostly ruled out by experiments

  (e.g., Kirsebom & Davids, 2011; O'Malley et al., 2011)

- **New physics**

  e.g.,Tsallis statistics (e.g., Kusakabe+18)

  Only Li shows discrepancy



Cyburt+16

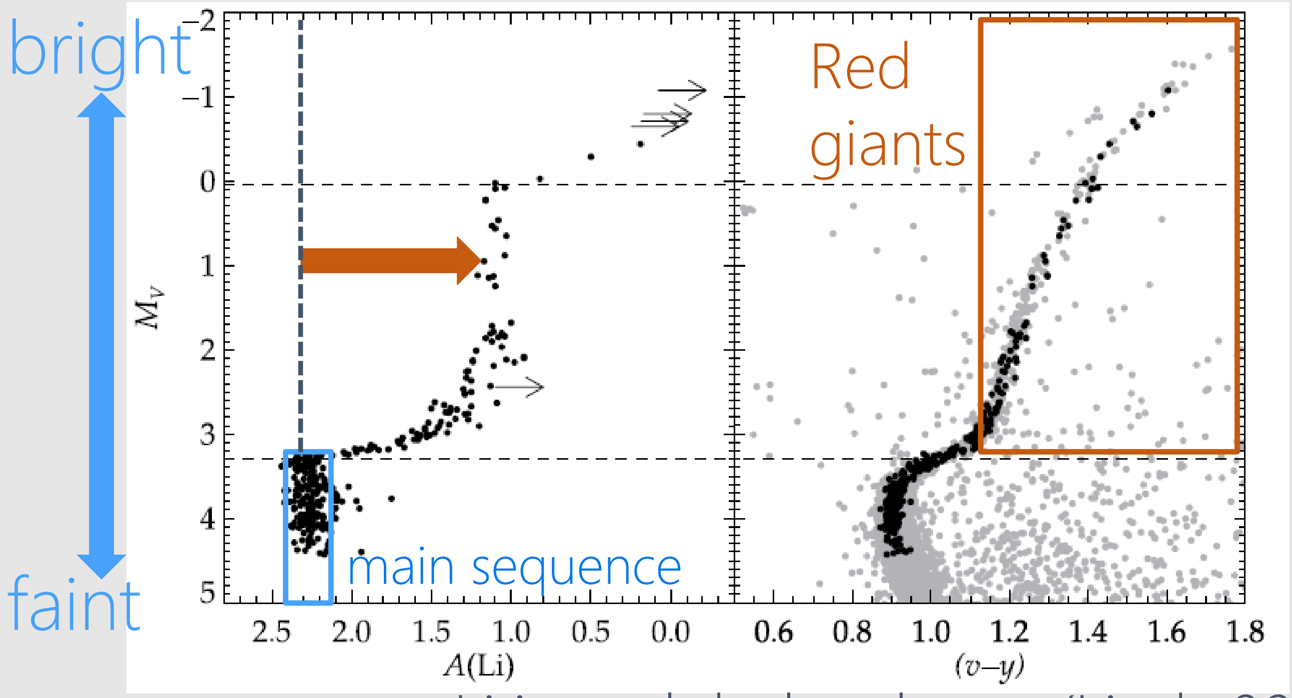
Does the Li abundance observation really reflect BBN?

Fragility of Lithium

Li destruction at 2.5×10^6 K (^{7}Li+p → ^{4}He+^{4}He)

Li abundance decreases when material from stellar interior pollutes the surface

e.g., red giants



Li in a globular cluster (Lind+09)

Suggestions to the Li problem

Proposed epoch of Li depletion

- **Before the formation of metal-poor stars** (Piau+06)

  Mixing of the primordial ISM with Li-free ejecta from first stars

- **Pre main-sequence phase** (Fu+15)

  Complete Li destruction during pre-MS + ISM accretion

- **Main sequence phase** (Richard+05)

  atomic diffusion + turbulent mixing during MS-phase

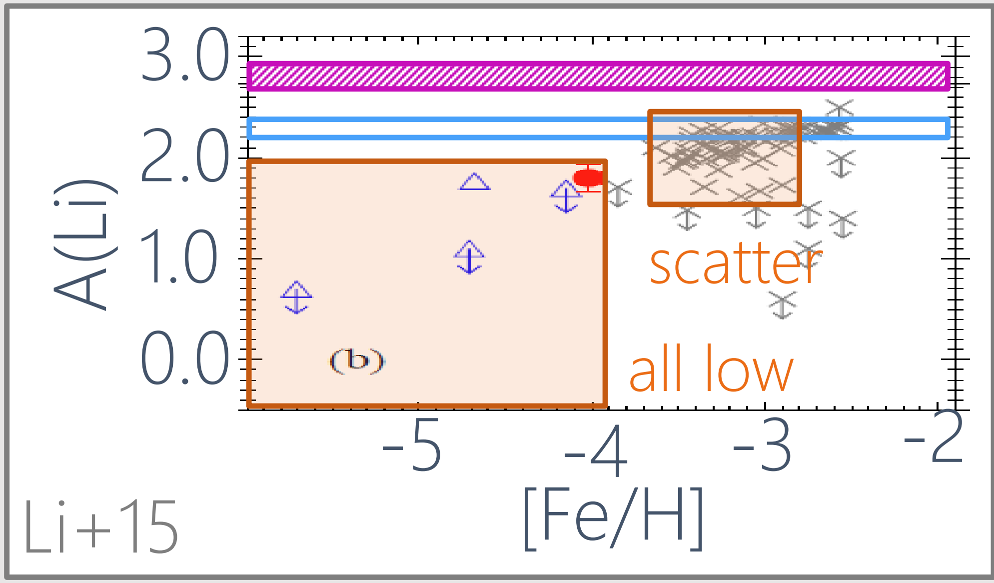
How to decrease Li abundance while keeping the small star-to-star scatter in Li abundance

Breakdown of the Plateau

Plateau doesn't extend to lowest metallicity

[Fe/H]~-3: Large scatter

[Fe/H]<-4: Low Li in all stars



Indicative of Li depletion in some of metal-poor stars

Related to the discrepancy between CMB and Spite plateau?

Require larger sample to clearly understand the nature of the breakdown

Goal

Observationally clarify the nature of the breakdown of Spite plateau

Observations of EMP TO stars

Extremely Metal-Poor ([Fe/H]<-3.0)

Turn-Off (Teff >5500 K)

Outline

Abundance determination

Lithium abundances at [Fe/H]<-3.5

EMP stars from SDSS/SEGUE

Lithium in relation to Carbon

Lithium abundances in CEMP-no stars

Abundance determination

Procedure of Abundance Analysis

Step 1. Measure the equivalent widths

Fitting absorption lines with Gaussian

Step 2. Estimate atmospheric params ($T_{\mathrm{eff}}, \log g$)

To determine evolutionary status

To calculate abundance from equivalent widths (Step 3)

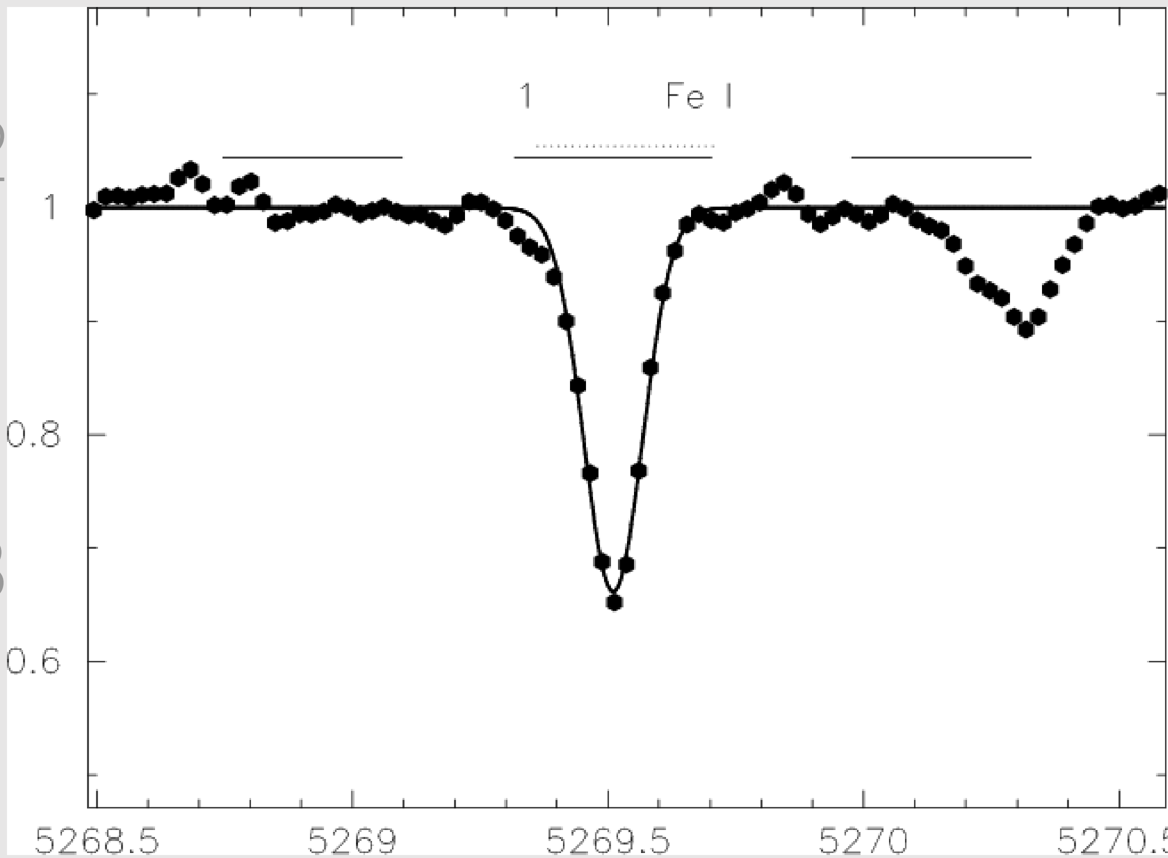
Step 3. Abundance calculation

Calculate abundance from equivalent widths

Procedure of Abundance Analysis

Step 1. Measure the equivalent widths

Fitting absorption lines with Gaussian



Step 2 … eff, log g)

…idths (Step 3)

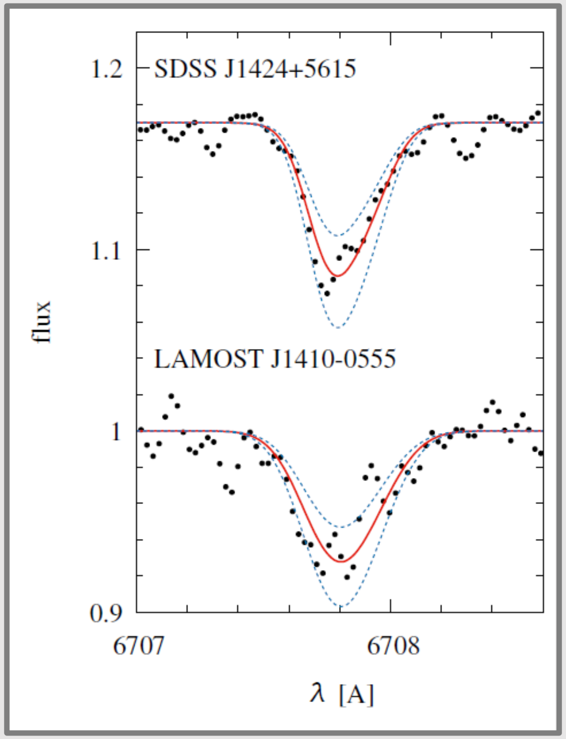
Step 3 … ths

Spectral synthesis

Due to asymmetry, Li absorption line can not be fit with Gaussian

-> Directly fit spectra with synthesized ones varying the abundance

Li absorption



Procedure of Abundance Analysis

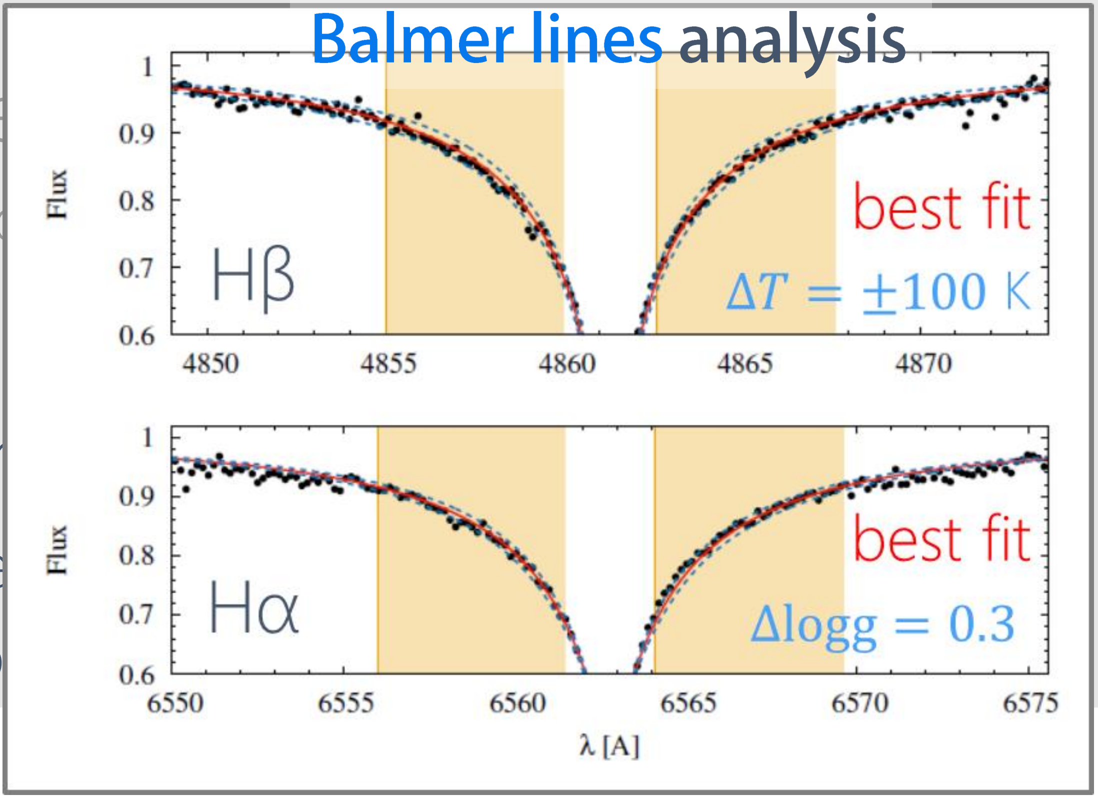
Step 1. Measure the

Fitting absorptio

Step 2. Estimate atr

To determine e

To calculate ab

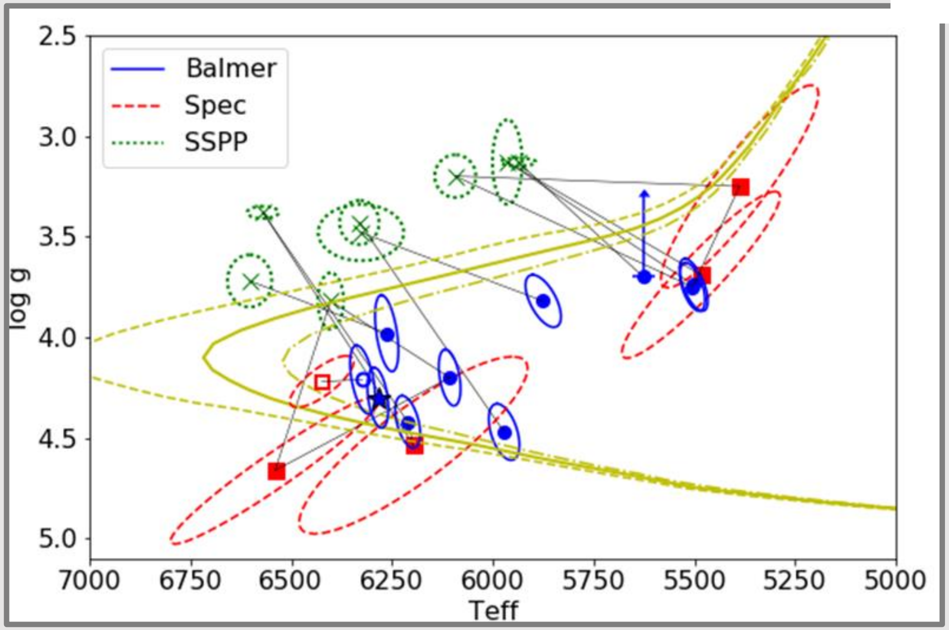


Other methods:

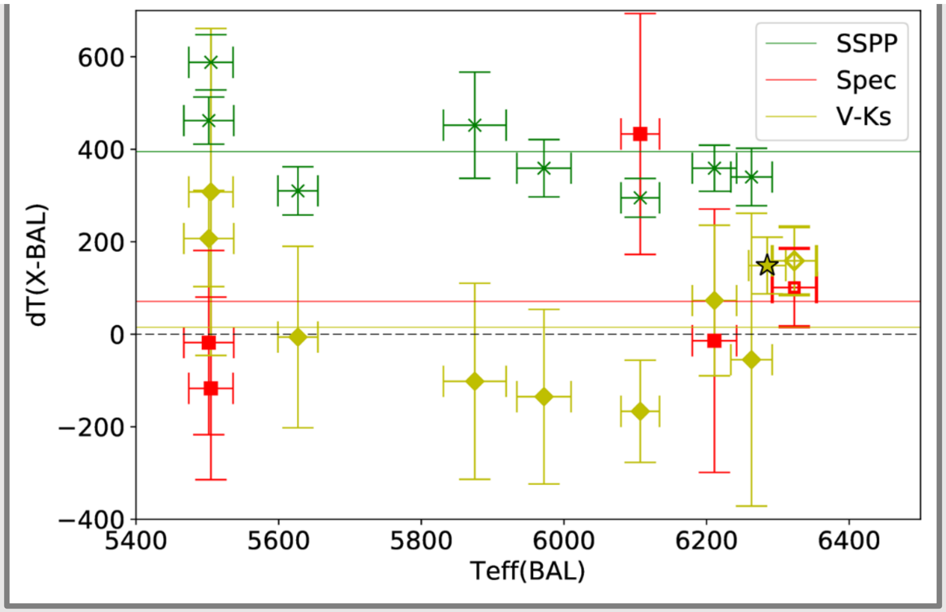
- Colors (for Teff)
- Pipelines of low-resolution spectroscopic survey
- Fe lines analysis
- Distance (log g)

etc.

Comparison of stellar parameters



Difference from Balmer lines analysis



Procedure of Abundance Analysis

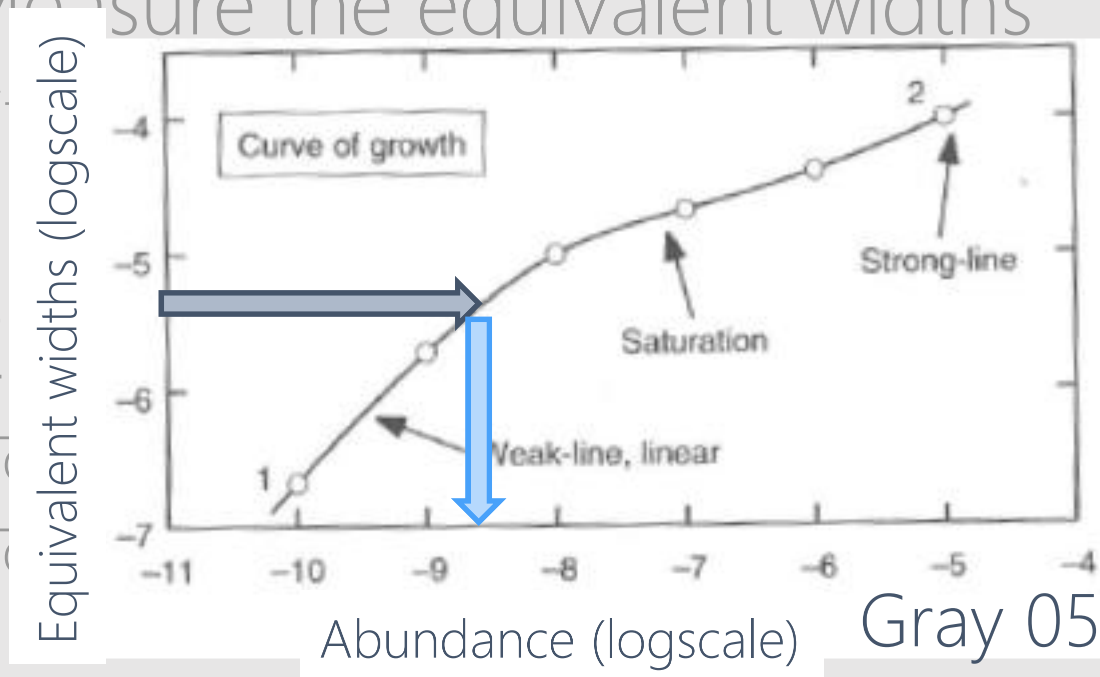
Step 1. Measure the equivalent widths

Fi

Step 2. E ... $T_{\rm eff}$, $\log g$)

T

T ... idths (Step 3)



Gray 05

Step 3. Abundance calculation

Calculate abundance from equivalent widths

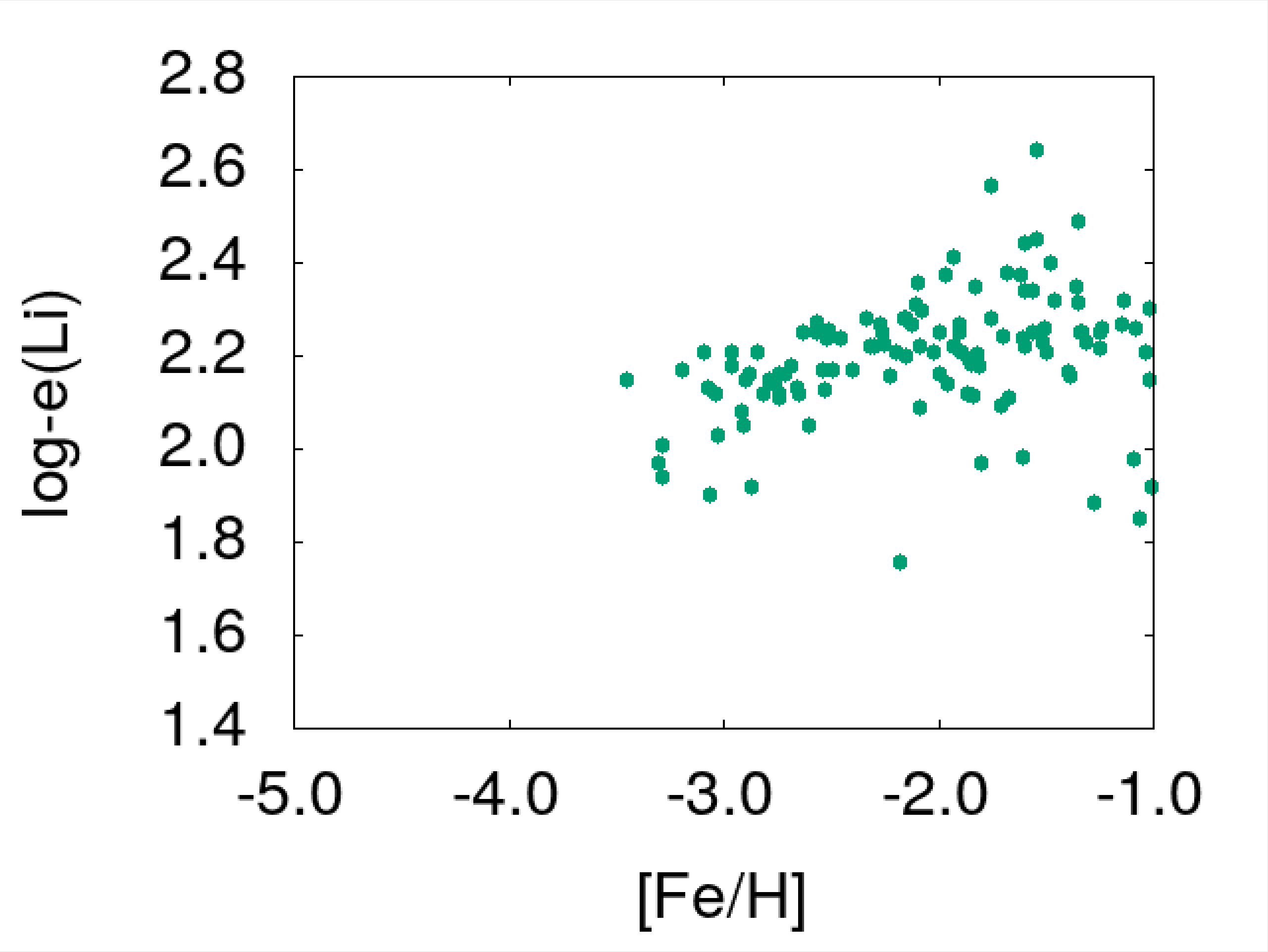
Lithium abundances at [Fe/H]<-3.5

(Extremely metal-poor turn-off stars from SDSS/SEGUE)

Matsuno, T. et al. (2017b, AJ, 154, 52)

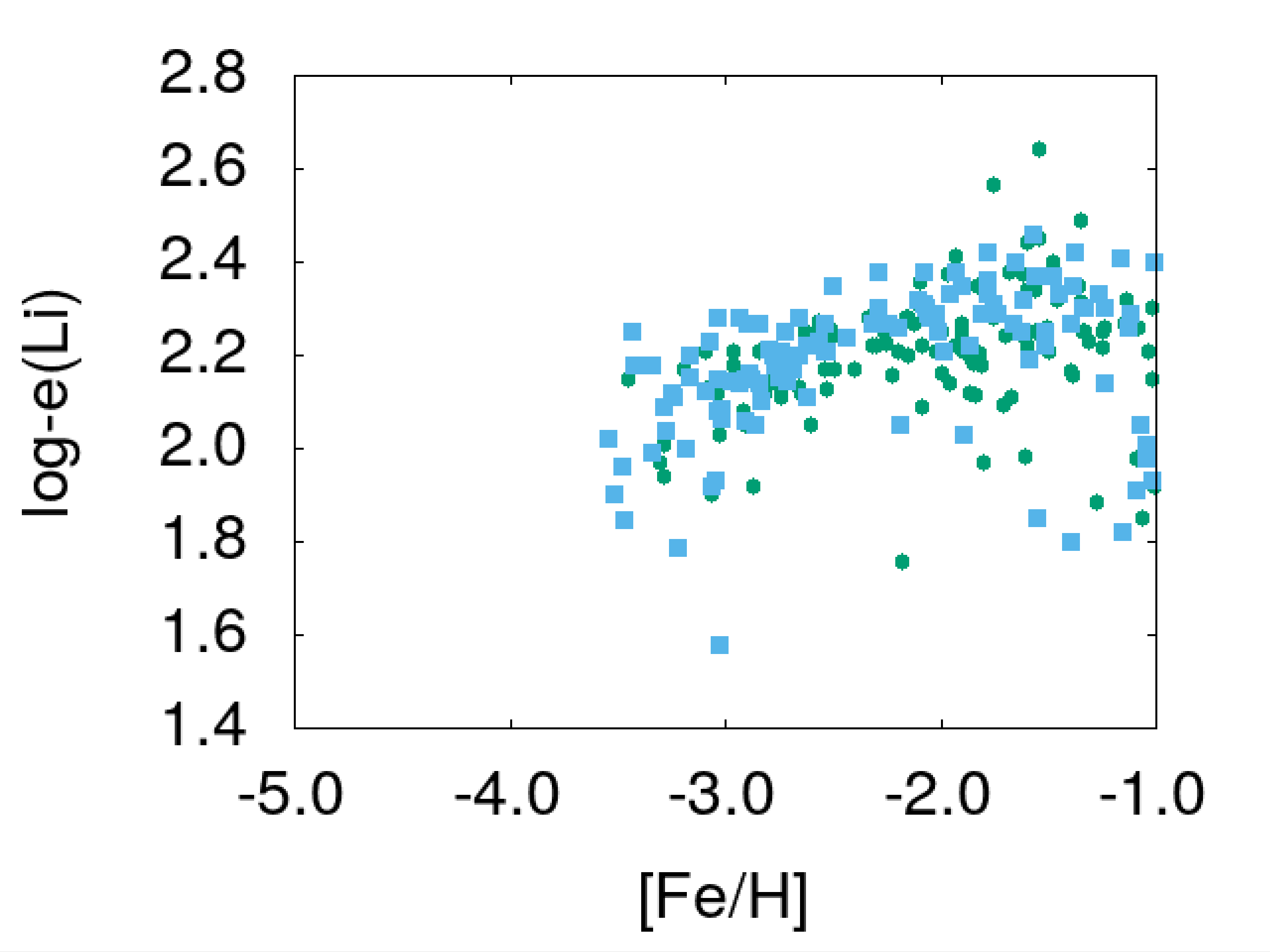
Previous measurements

Before 2008



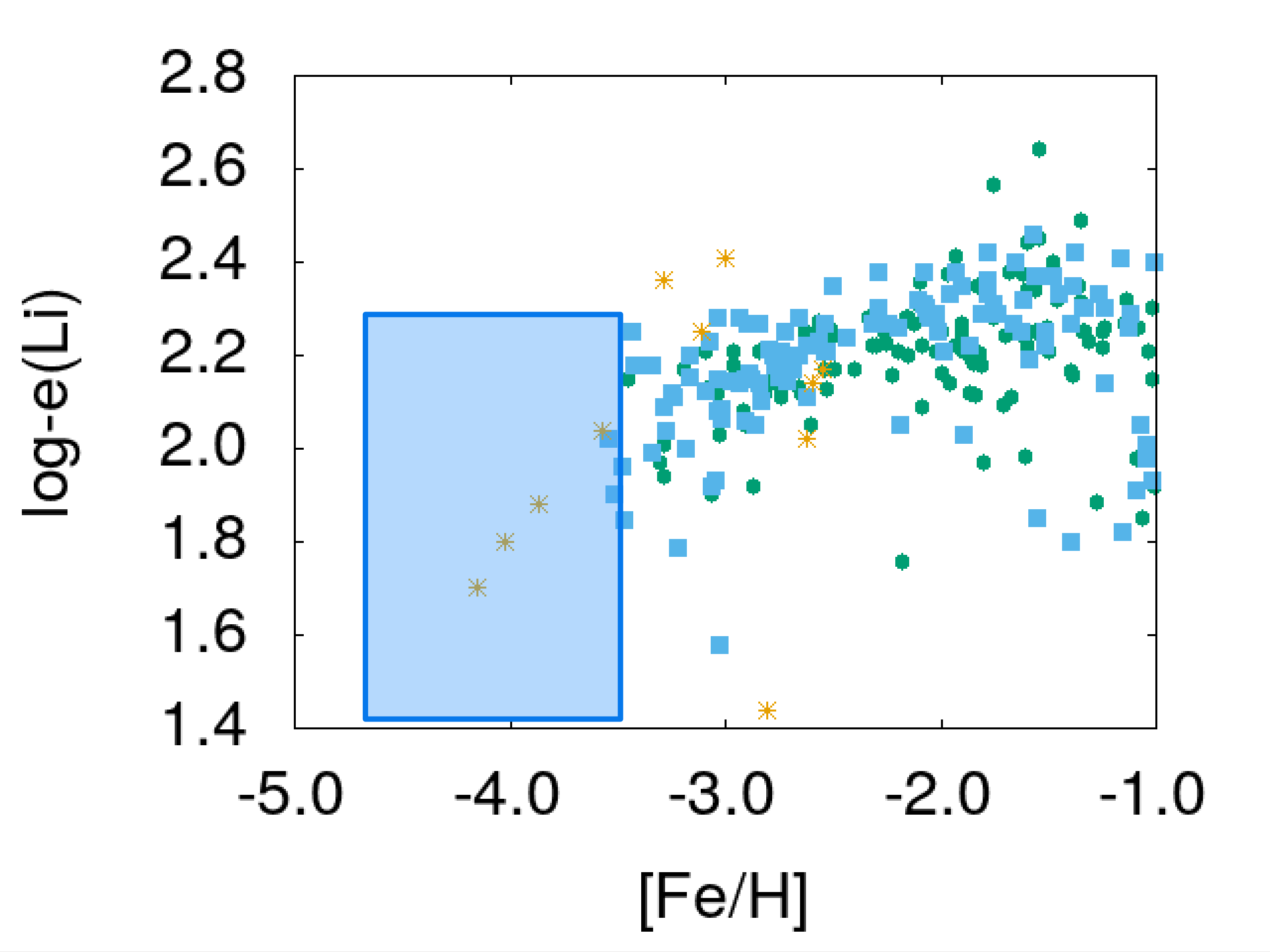
Previous measurements

Before 2013

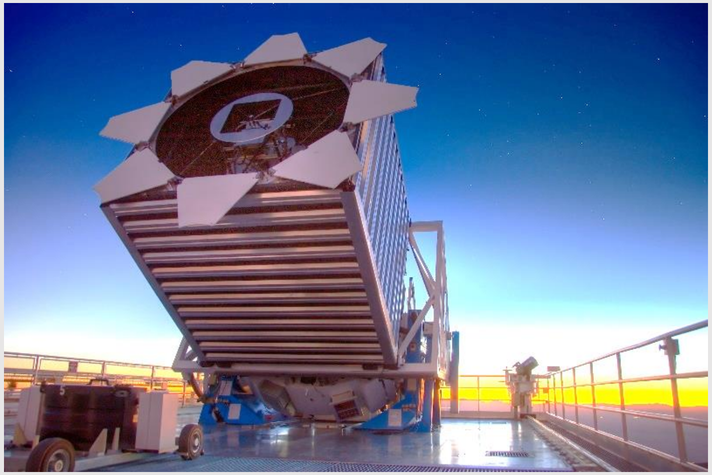


Previous measurements

Before 2016



Targets & Observations



Eight stars with [Fe/H]<-3.0

In particular, we focus on [Fe/H] < -3.5

Aoki et al. 2013

Subaru/HDS observations (R~36,000, S/N~20-30)

for 137 metal-poor stars found in SDSS/SEGUE survey

Further follow-up observation

Higher quality data (R~60,000, S/N≳50)

-> This work

Results: Metallicity

7 out of 8 stars are [Fe/H]<-3.5

Object	[Fe/H]
SDSS J1424+5615	-3.10
SDSS J1640+3709	-3.54
SDSS J1036+1212	-3.62
SDSS J2349+3832	-3.73
SDSS J0120-1001	-3.84
SDSS J2005-1045	-3.86
SDSS J1522+3055	-3.94
SDSS J2309+2308	-3.96

Differential Analysis

Source of uncertainty in abundance analysis

Approximations in model atmosphere
(local thermodynamical equilibrium, 1D plane parallel)
Uncertainty in atomic data

Differential analysis

$$A \simeq \cancel{-\log(gf)} \cancel{- \log \lambda} + \chi\theta + \log\left(\frac{EW}{\lambda}\right) \cancel{+ const.},$$

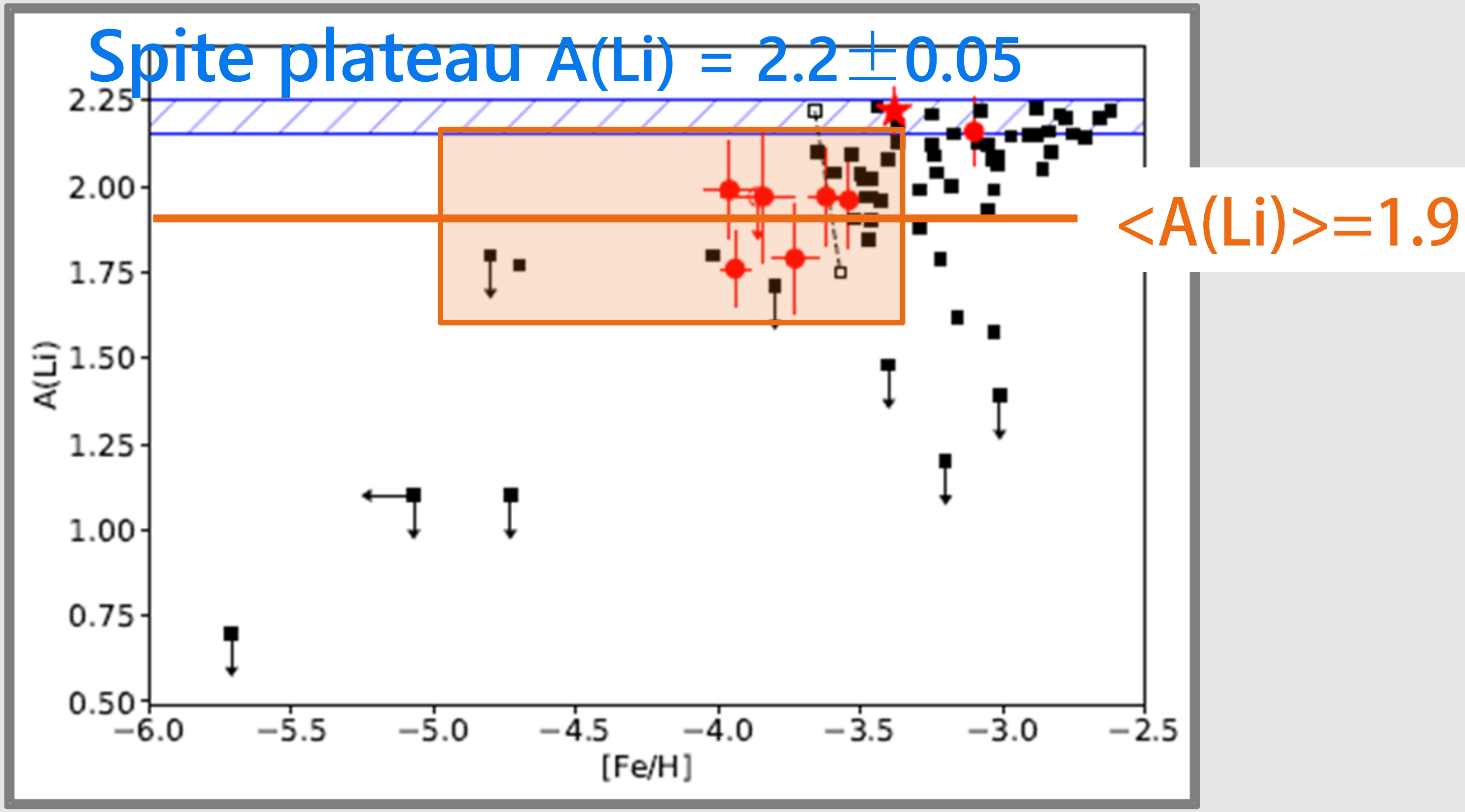
where $\theta = 5040/T_{\mathrm{eff}}$.

Cancels out deviation from the approximations

Particularly effective between stars with similar stellar params.

Lithium abundance at [Fe/H]<-3.5

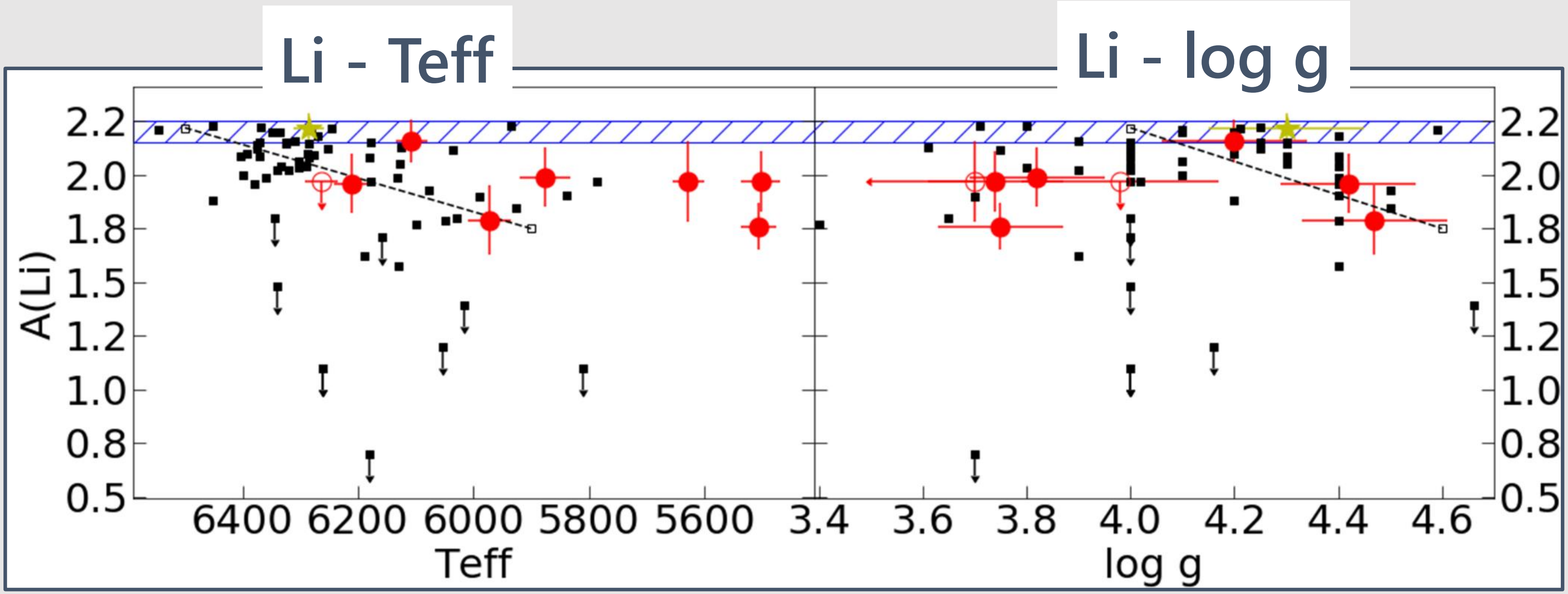
■ literature
● This work



All stars with [Fe/H] < -3.5 have Li abundance lower than the plateau

No significant scatter in Li abundance ($\sigma_{A(Li)}$ ~0.10 dex)

Li and Atmospheric Parameters



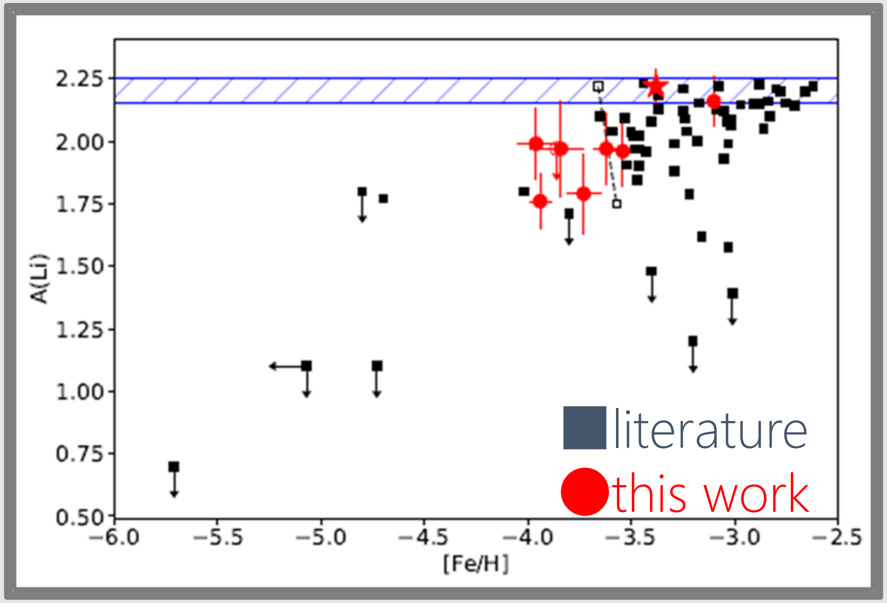
Li is independent from Teff or log g

-> Li abundance is not relevant to stellar evolution nor mass

Lithium Abundance at [Fe/H]<-3.5

- All stars have low Li abundance at [Fe/H]<-3.5
- No significant scatter in Li abundance
- Li abundance does not correlate with any properties

Li abundance seems to only correlate with metallicity



Lithium in relation to Carbon

(Lithium in CEMP-no stars)

Based on Matsuno et al. (2017a, PASJ, 69(2), 24)

Carbon Enhanced Metal-Poor Stars (CEMP)

Carbon-Enhanced Metal-Poor stars ([C/Fe]>0.7)

Many metal-poor stars show carbon enhancements

CEMP-no

without *s*-process excess

[Ba/Fe]<0.0

C-excess is likely due to first stars

>80% at [Fe/H]<-4

CEMP-s

with *s*-process excess

[Ba/Fe]>1.0

As a result of mass transfer from evolved companion

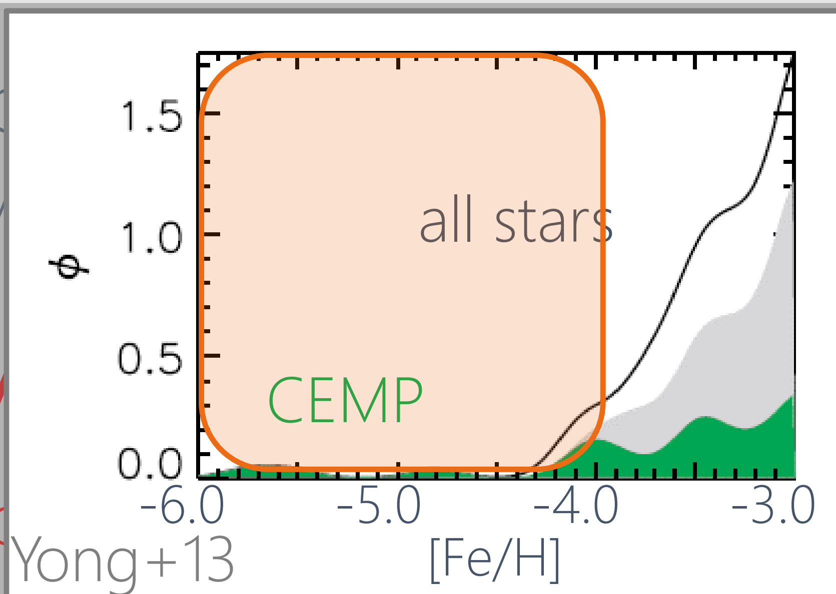
Carbon Enhanced Metal-Poor Stars (CEMP)

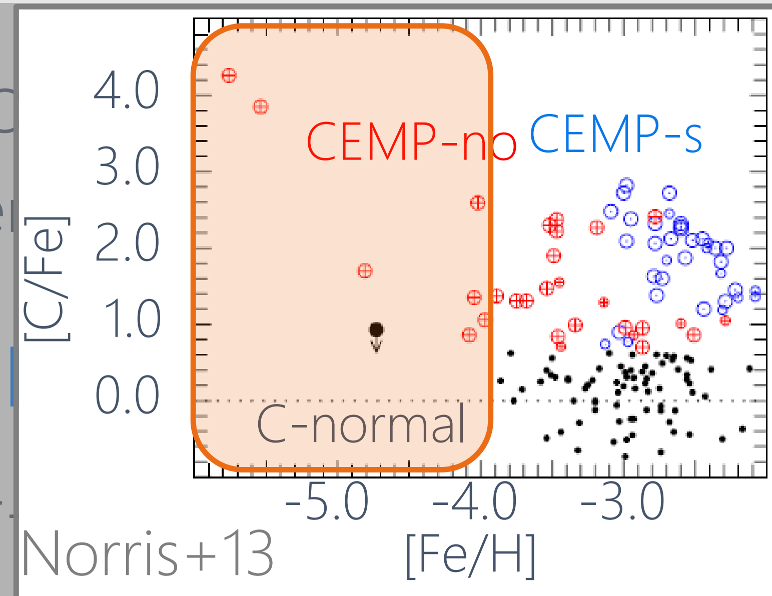
Carb

Many

CEM

witho





s-

[Ba/Fe]<0.0

[Ba/

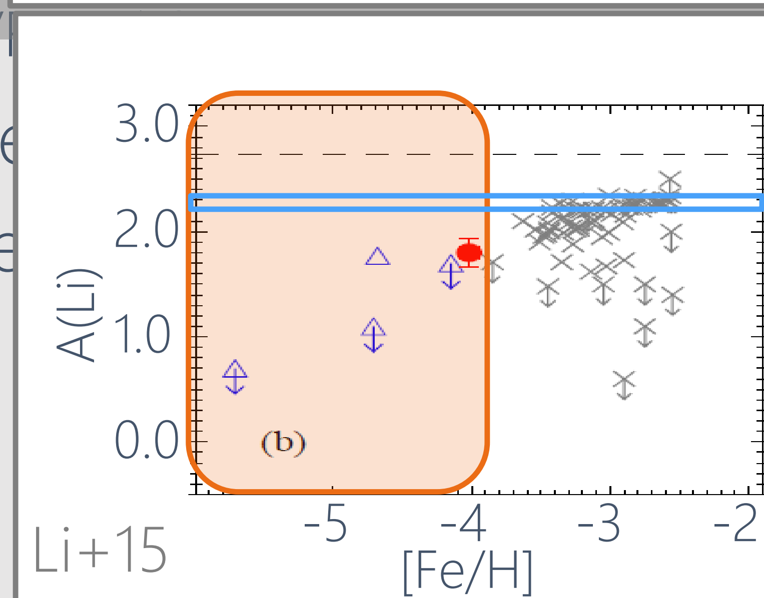
C-excess is likely due to first stars

As a re

from e

>80% at [Fe/H]<-4

All stars show low –Li abundance



CEMP-no and Li

- Most of stars are CEMP-no
- All stars show low Li abundance

at [Fe/H]<-4

Speculation on a connection between the two results

-> Breakdown ([Fe/H]≲-2.5) might be
due to increasing fraction of CEMP-no

Li measurements in CEMP-no stars

Frebel+08, Bonifacio+15 etc. -> low Li

However, most of them are[Fe/H]<-4

Which of low metallicity or CEMP-no nature is the fundamental cause of low Li abundances?

Targets & Observations

-3.5<[Fe/H]<-2.0

- Many C-rich stars and C-normal stars
- Plateau breaks down at this metallicity

Target

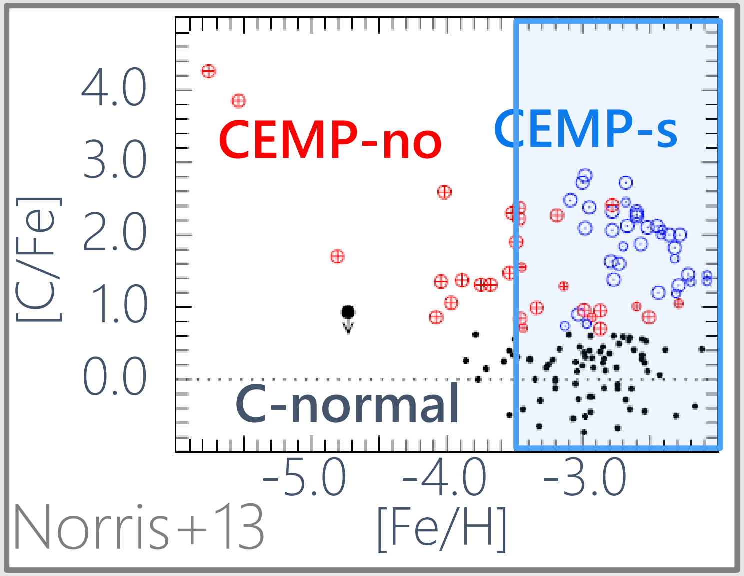
2 CEMP-no stars

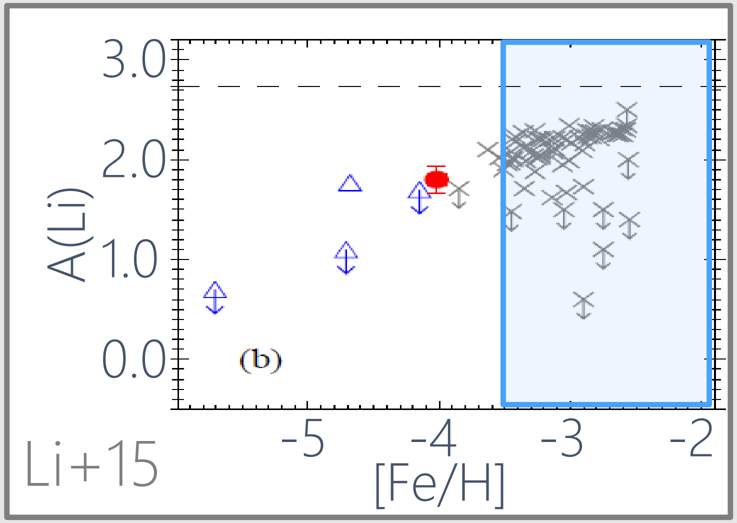
with [Fe/H]~-3, Teff~6000 K

Observations

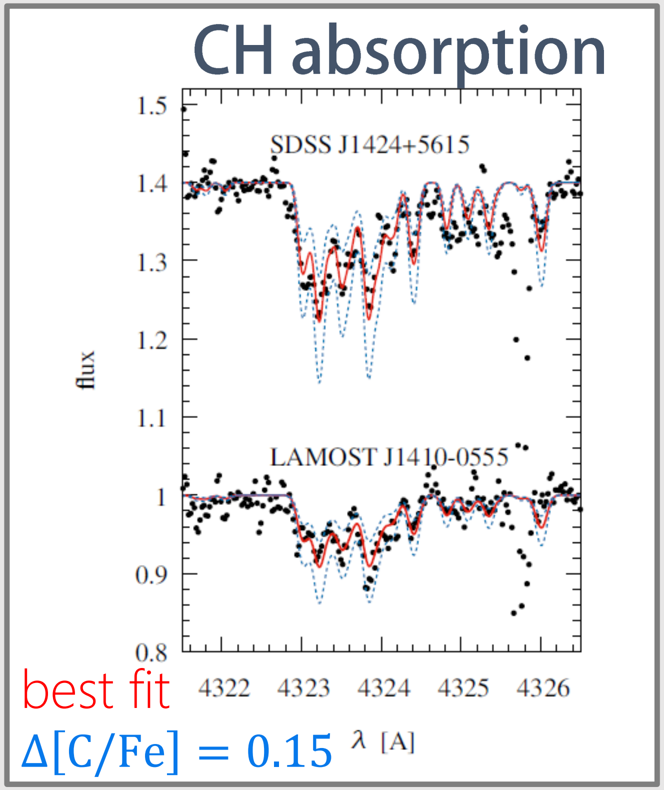
Subaru HDS

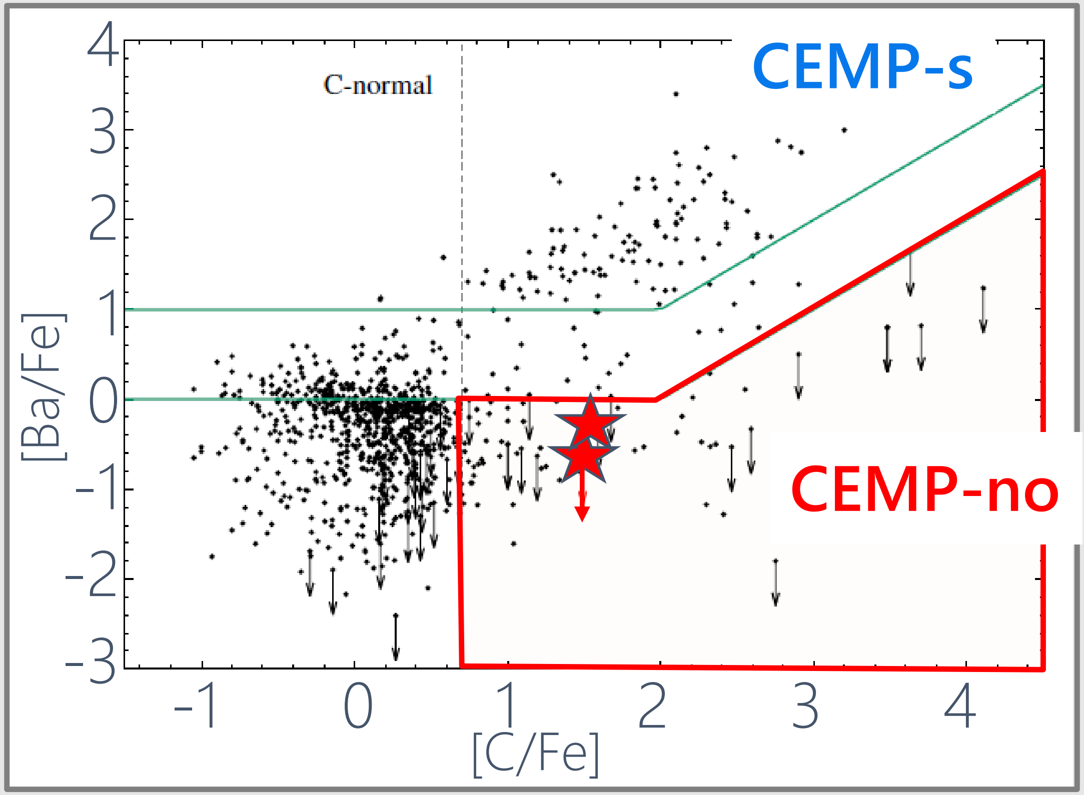
R~60000, S/N~100





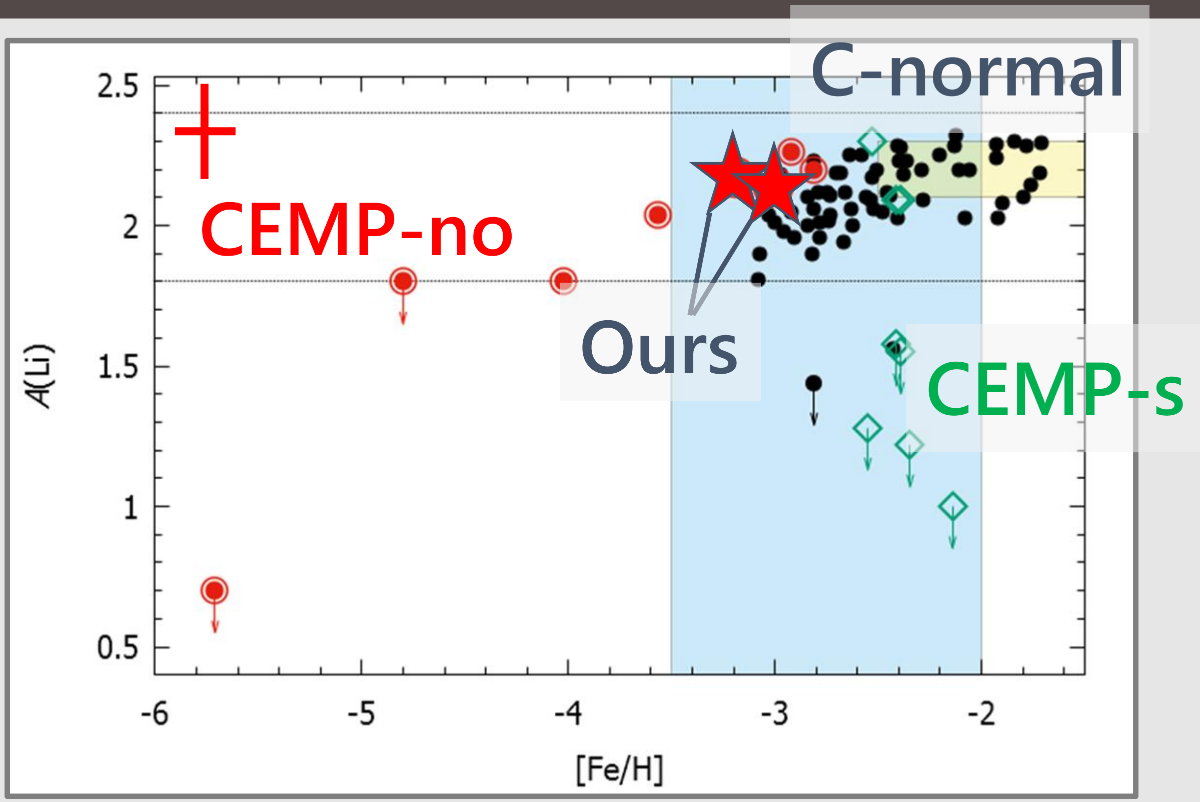
C, Ba abundance





Both of the 2 objects are C-rich, Ba-poor -> **CEMP-no**

Lithium in CEMP-no Stars



As a result of mass transfer from evolved stars (Masseron+12)

Li abundance of CEMP-no stars are similar to that of C-normal stars

CEMP-no and breakdown

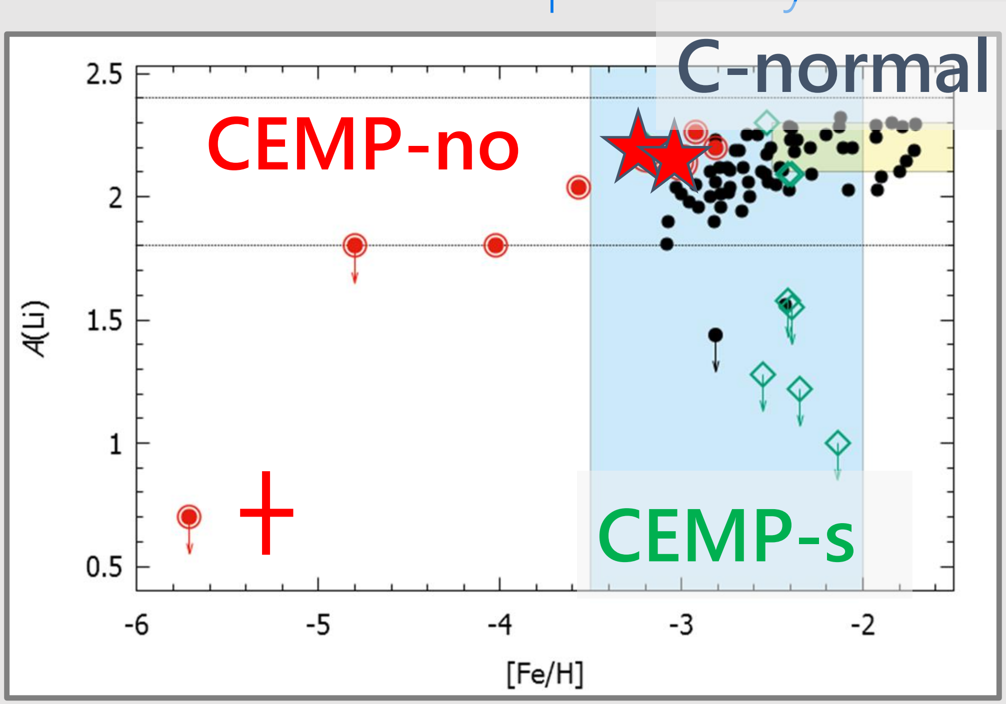
Do CEMP-no stars necessarily show low Li abundance?

No.

Li abundance of CEMP-no stars are similar to that of C-normal stars at [Fe/H]~ -3

->Breakdown ([Fe/H]~-3) is not related to the large fraction of CEMP-no

-> C-excess and low-Li at [Fe/H]<-4 are caused independently



Results and Models

Results of the present study

[Fe/H]<-3.5: Average Li abundance is lower than plateau

[Fe/H]<-3.5: Scatter is insignificant ($\sigma_{A(\mathrm{Li})}$ ~0.10 dex)

[Fe/H]<-2.5: breakdown is unrelated to CEMP-no fraction

Li abundance only correlate with stellar metallicity

Constraints on models

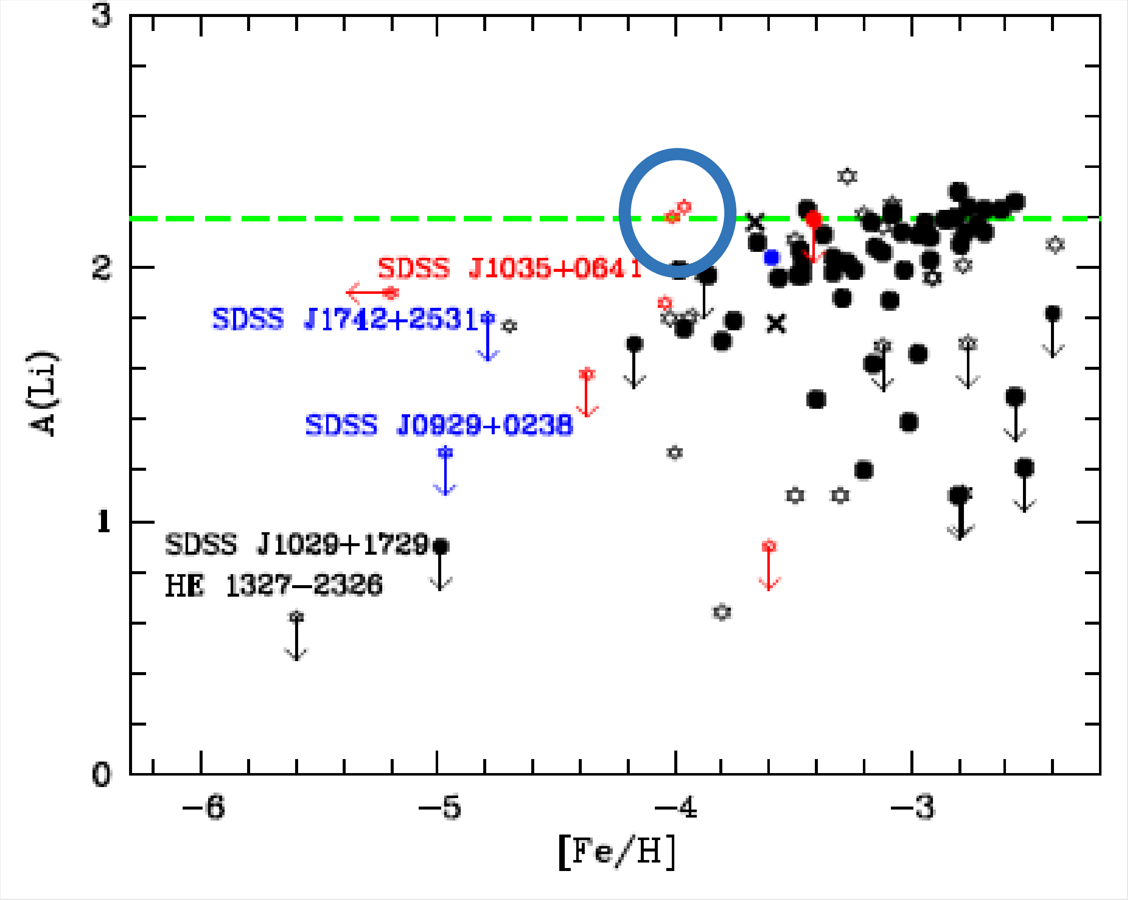
- Before the formation of metal-poor stars (first stars; Piau+06)
- Pre main-sequence phase (Fu+15)
- Main-sequence phase (Richard+05)

All need fine-tuning of a parameter

-> Need to understand the physical origin of the parameter
as well as application/tuning to lowest metallicity

Current situation

Discovery of normal Li stars at [Fe/H]~-4?



Bonifacio+18

More sample -our ongoing survey-

Precise abundance is hardly available at [Fe/H]<-3.0

-> **Find out bright extremely metal-poor stars!**

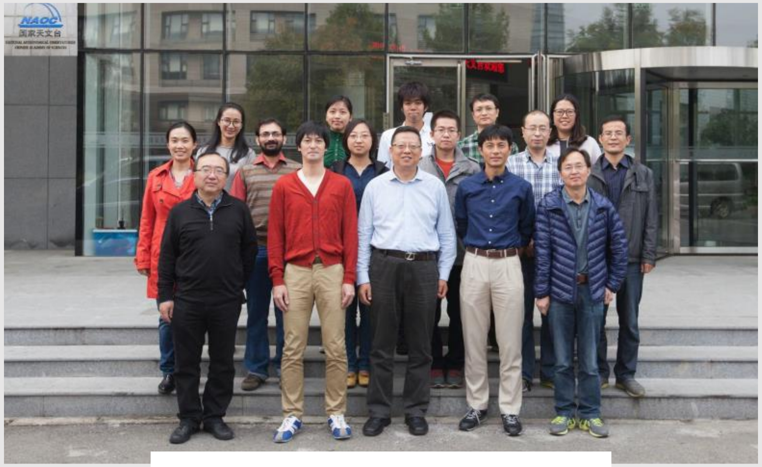
LAMOST-Subaru study for 400 metal-poor stars

cf. LAMOST sample: 12-15 mag, SDSS/SEGUE: 14-16 mag

Observation has finished! (Li, H.N., Aoki, W., Matsuno,T. et al.)

e.g., More CEMP-no stars with normal Li (Zhang+ in prep.)

LAMOST telescope

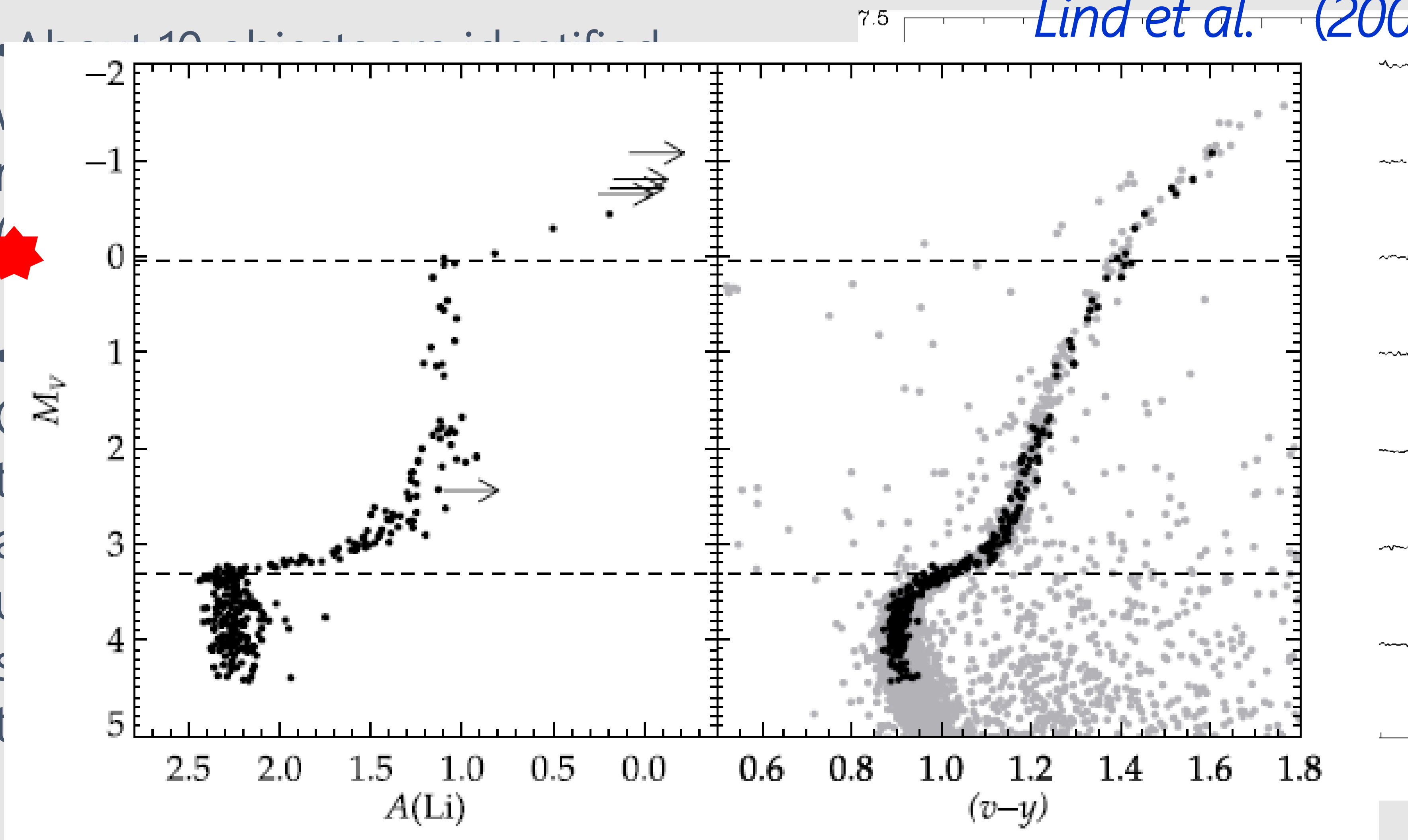


meeting at Beijing

Li-rich stars found by LAMOST/Subaru

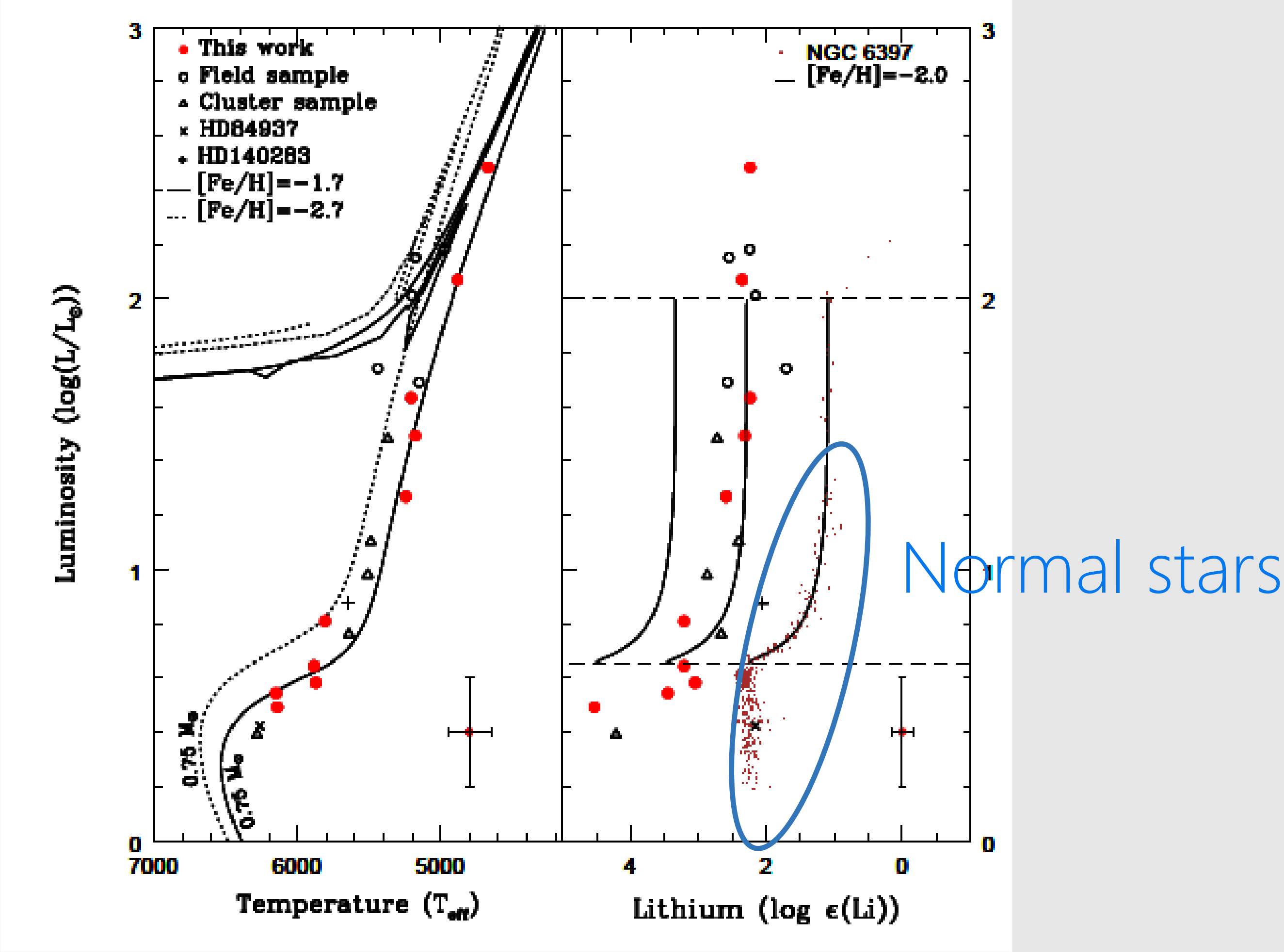
(c) Aoki, W.

Lind et al. (2009)



Li-rich stars

Li, H.N., Aoki,W., Matsuno,T. et al. (2018, ApJL)



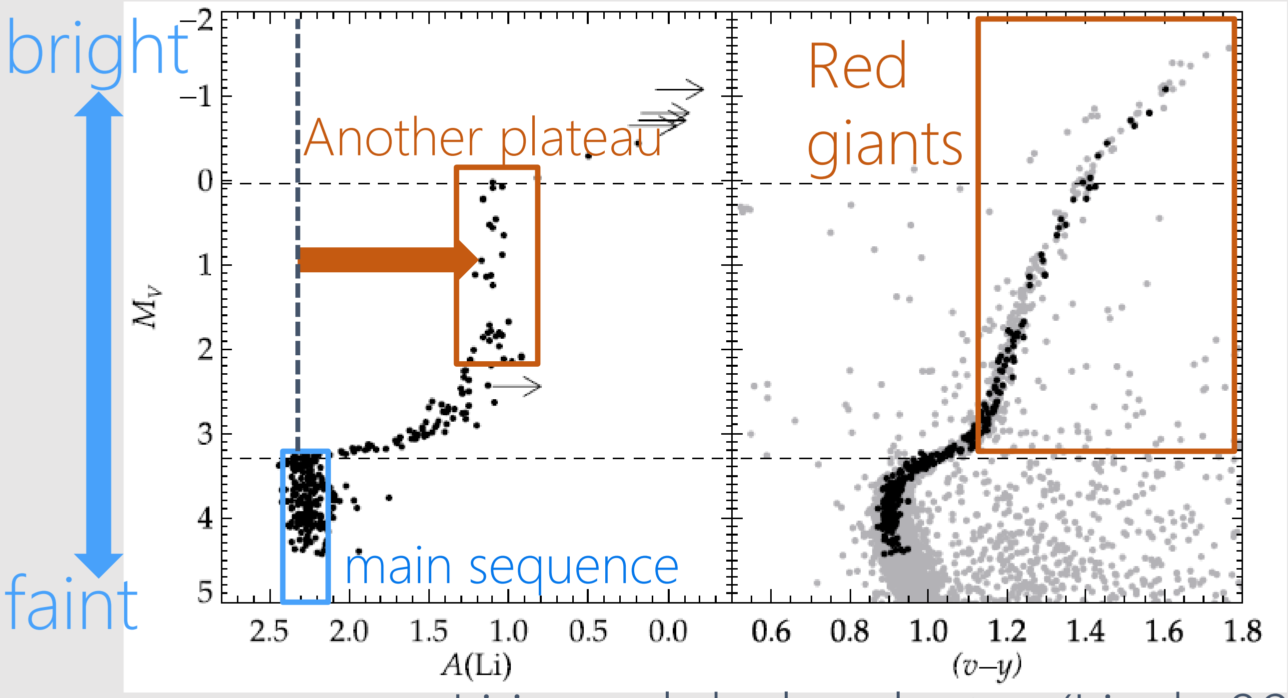
Li abundance of Li-rich stars evolves similarly to normal stars

-> Li-enrichment during main-sequence

What's next?

Li abundance of red giants as an independent probe

(Mucciarelli+12)



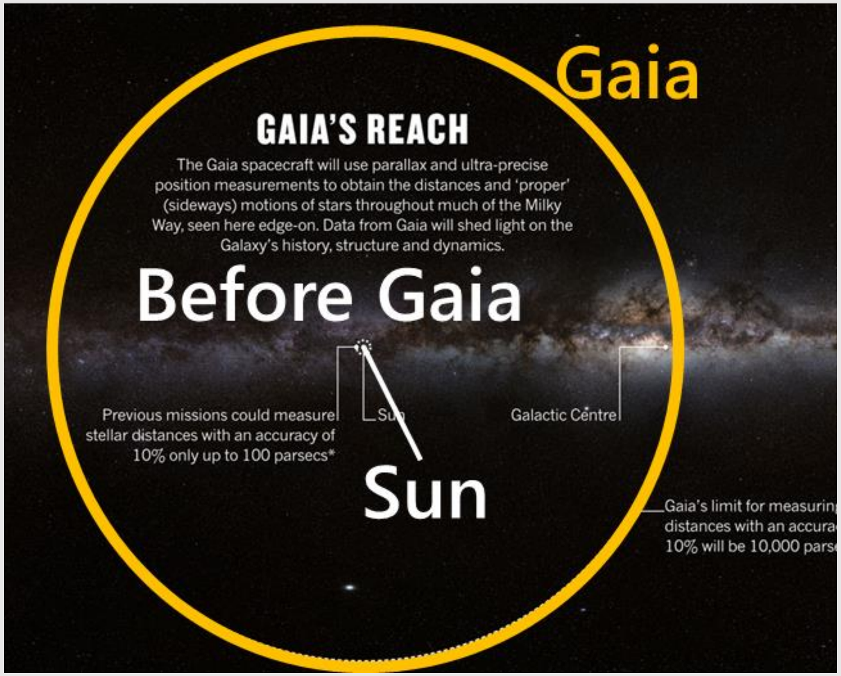
Li in a globular cluster (Lind+09)

Let's make use of another plateau of red giants

We have to put all the stars at the same distance

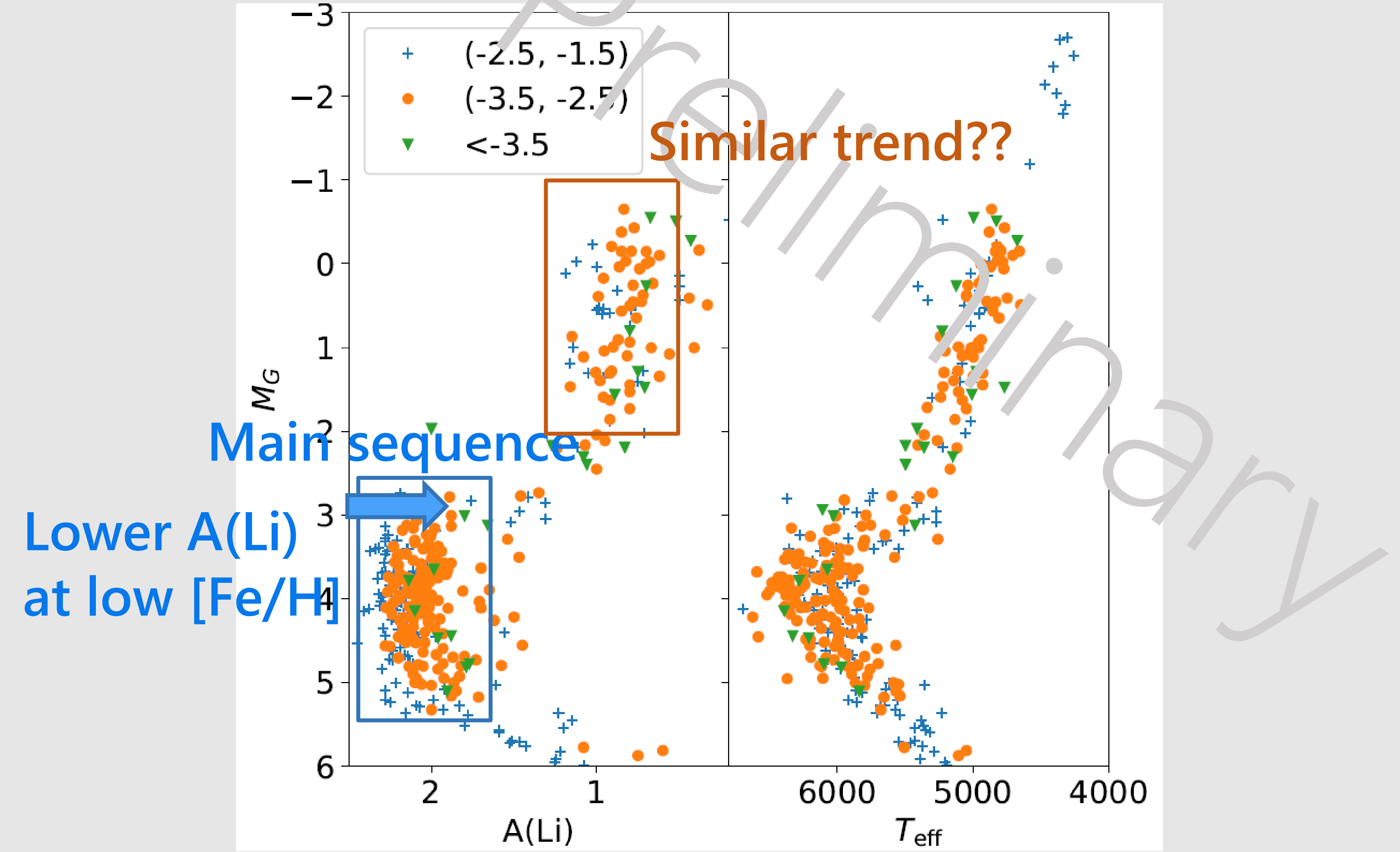
Gaia

Gaia measures distance and magnitude of stars (the second data release happened on 25 April 2018)



Gaia is also important to study stellar motions in the Galaxy (this is the main reason for me to come here!)

Li abundance of red giants



Summary

- **Observational understanding of the breakdown**

  - Li abundance at [Fe/H]<-3.5 is uniformly low

  - Breakdown is not related to a large fraction of CEMP-no

  Li abundance correlates only with metallicity

- **Constraints on models**

  Require model understanding and application for low metallicity stars

- **Futures**

  Our ongoing project and Gaia will provide new insights

Li Depletion Models

All models are suggested to explain the discrepancy between the Big Bang and the Spite plateau

Before the formation of metal-poor stars (Piau+06)
MP stars are formed from the mixture of Li-free ejecta from first stars and ISM with BBN composition

Pre-MS stage of metal-poor stars (Fu+15)
Complete Li-destruction during pre-MS phase and later recovery by ISM accretion

During MS phase of metal-poor stars (Richard+05)
Atomic diffusion + additional mixing
(see also Korn+06,07, Gruyters+13)