JSPS-CAS joint program:
Exploring the early chemical evolution of the Milky Way with LAMOST and Subaru

Subaru intensive program S16A-119I: LAMOST/Subaru study for 500 very metal-poor stars

What can we learn from metal-poor stars

- **Nucleosynthesis by first stars**

  →mass and evolution of first stars, and super nova explosion

- **Early chemical evolution**

  →constraints on galaxy formation models

- **Individual nucleosynthesis processes**

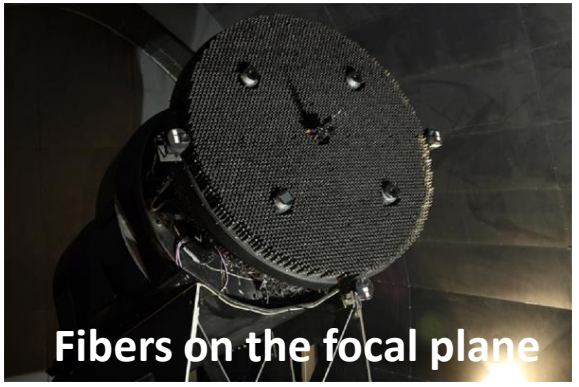
  big-bang nucleosynthesis (Li), heavy elements

- **Evolution of low-mass stars and binary systems**

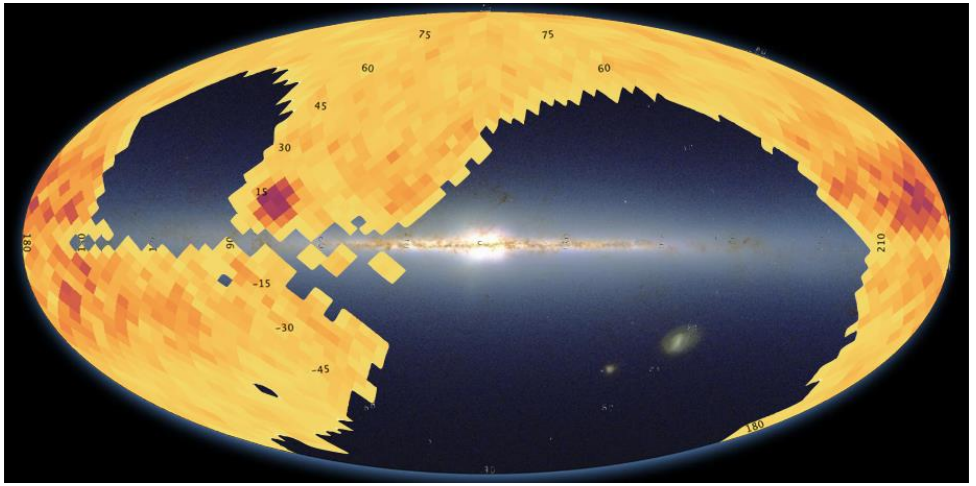
Searches for metal-poor stars and follow-up high-resolution spectroscopy

LAMOST survey

-*R*=1800
-4000 fibers
-r<19



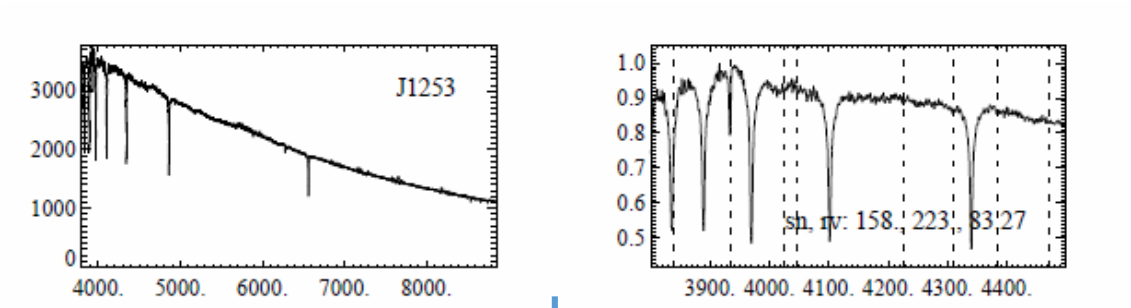
Data Release 5 (DR5):
7.5 million spectra including 5.3 million AFGK stars



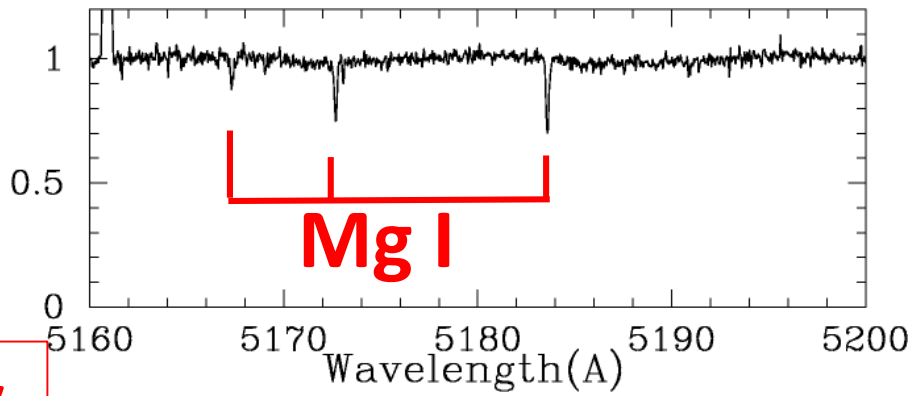
Target selection: random selection for a given magnitude/temperature range
cf. SDSS/SEGUE

Target selection from LAMOST sample

LAMOST medium resolution spectra



Subaru high-resolution follow-up spectroscopy



J1253+0753 [Fe/H]=-4.0 main-sequence turn-off

LAMOST covers relatively bright stars (V<14)

Members in Japan

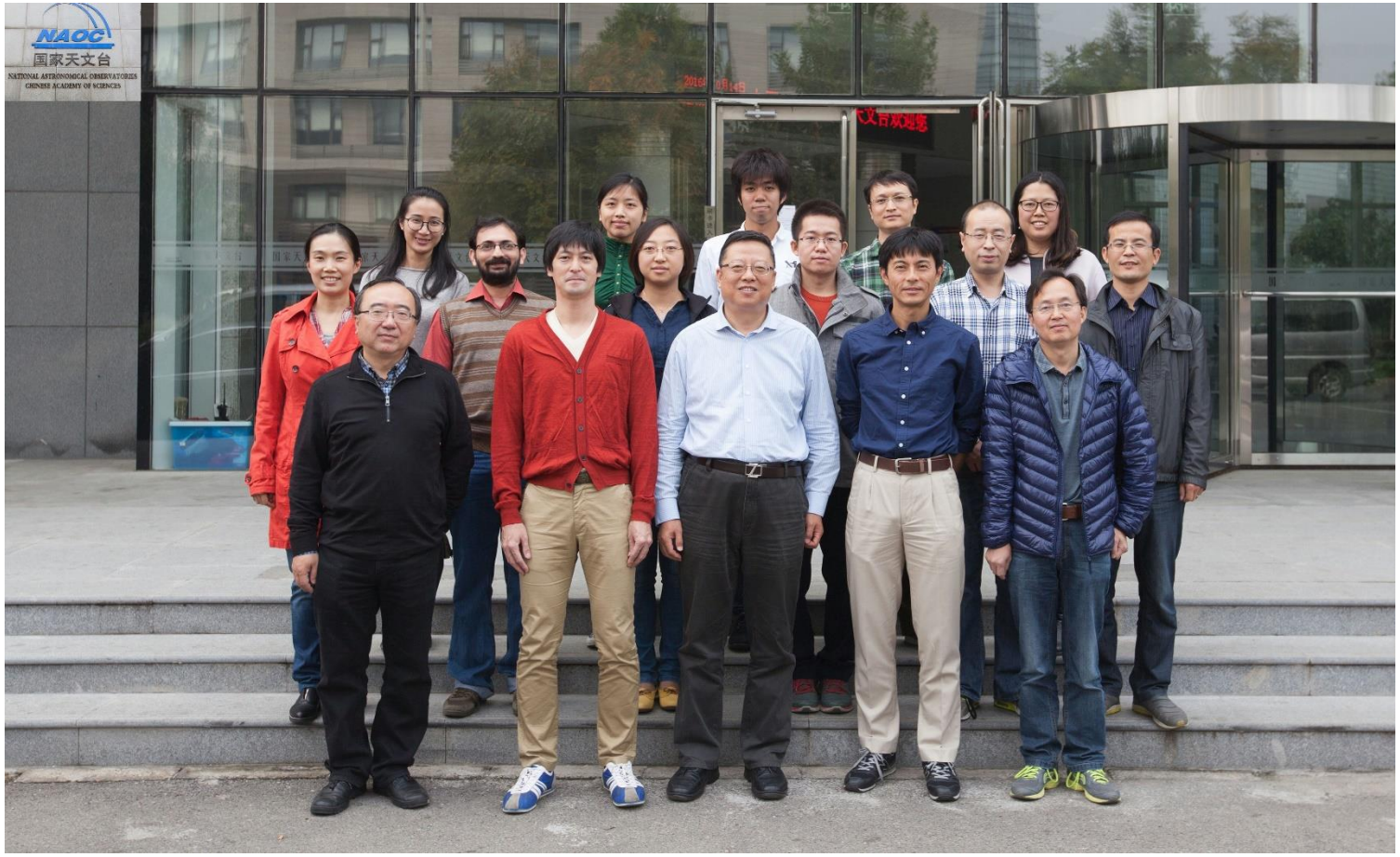
Wako Aoki 青木 和光	NAOJ/TMT-J Associate professor	Stellar abundances, high-resolution spectroscopy
Nobuo Arimoto 有本 信雄	Seoul University professor	Galactic Archaeology
Takuma Suda 須田 拓馬	Univ. of Tokyo Assistant professor	Stellar evolution Database
Satoshi Honda 本田 敏志	Univ. of Hyogo researcher	Stellar abundances, high-resolution spectroscopy
Miho Ishigaki 石垣美歩	Univ. of Tokyo, IPMU researcher	Stellar abundances, high-resolution spectroscopy
Tadafumi Matsuno 松野 允郁	Sokendai/NAOJ PhD student	Stellar abundances, high-resolution spectroscopy
Misa Aoki 青木 みさ	ESO PhD student	Stellar abundances, high-resolution spectroscopy

NAOC team

趙　剛 Gang Zhao	Chief Professor	Chinese PI
陳玉琴 Yuqin Chen	Professor	Galactic evolution, clusters
趙景昆 Jingkun Zhao	Professor	Streams, moving groups
李海宁 Haining Li	Associate Professor	MP stars, target selection, observation
談克峰 Kefeng Tan	Associate Professor	Chemically peculiar & super Li-rich stars
邢千帆 Qianfan Xing	Assistant Professor	Alpha-abnormal stars, observation
翟　萌 Meng Zhai	PhD. Student	Data analysis, observation
張世琳 Shilin Zhang	PhD. Student	Data analysis, observation
施建荣 Shi Jianron	professor	Li-rich giants / metal-poor stars in Kepler field

Norbert Christlieb (Heidelberg)

2016 October collaboration meeting in Beijing （北京)



2017 October collaboration meeting in Weihei (威海)

Subaru intensive program: LAMOST/Subaru study for 500 very metal-poor stars

- **Searches for rare but key objects:**

  -signature of first stars

  -neutron-capture element-enhanced stars

- **Statistics of very metal-poor stars:**

  -metal-poor tail of the metallcity distribution function

  -binary frequency from double-lined binaries

  -trend and scatter (or clustering) of elemental abundance ratios

Subaru intensive program: LAMOST/Subaru study for 500 very metal-poor stars

→ double the sample of very metal-poor stars with chemical abundance measurements by homogeneous analysis

- **Main sample**
  -Extremely metal-poor ([Fe/H]<-3) stars
  -Bright (V<14) very metal-poor ([Fe/H]<-2) stars
  -Li-enhanced very metal-poor stars

- **Some specific topics**
  -α-rich/poor stars
  -Li-rich giants
  -Moving group members

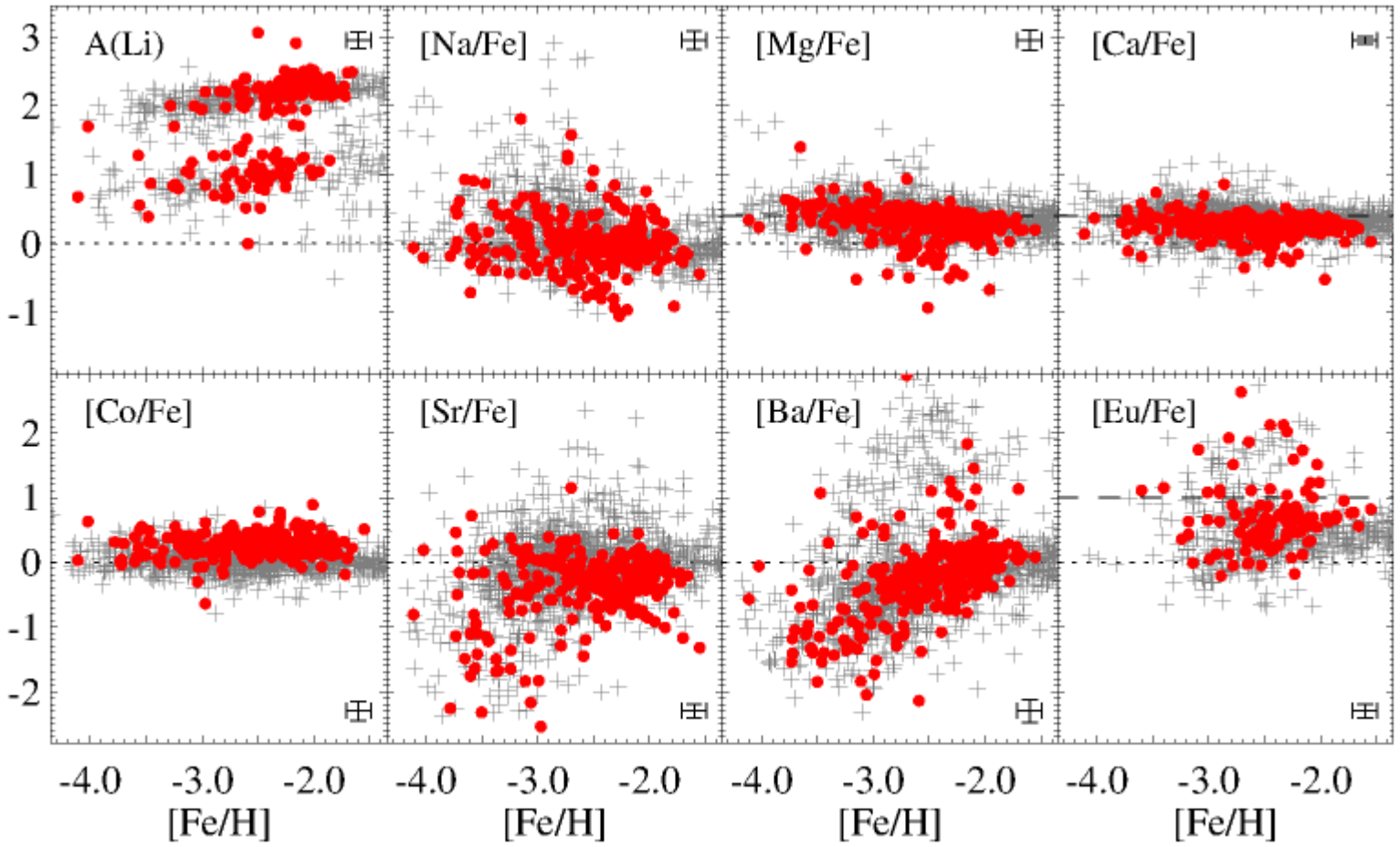
Intensive program: observations

	Date	Weather		# of stars
2016	April 26 (half night)	Clear		12
	April 27 (half night)	Clear		12
	May 20	Clear		24
	May 22	Clear		35
	May 23	Clear		37
	May 27	Clear		22
	May 28	Clear	Partially lost by high humidity	26
	Nov. 16	Clear	2” seeing	35
	Nov. 17	Clear	Telescope trouble (-3 hours)	14
	Nov. 18	Clear	Telescope trouble (-1 night)	0
	Nov. 19	Clear/cloudy	Partially lost by high humidity	17
2017	Feb. 15	Clear		29
	Feb. 16	Clear		33
	Feb. 17	Clear		30
	Feb. 18	Clear	CCD readout trouble	21
	Feb. 19	Clear/cloudy		31
	Aug. 1 (half night)	Clear	Telescope trouble (-0.5 night)	1
	Aug. 2 (half night)	Clear		16
	Aug. 3 (half night)	Clear	Setup=StdBc	5
	Aug. 4 (half night)	Clear		21
	Aug. 5 (half night)	Clear		11

Large sample of metal-poor stars

Elemental abundances for >250 very metal-poor stars (including stars observed in normal programs) have been obtained

H-N. Li



Li-enhanced very metal-poor stars

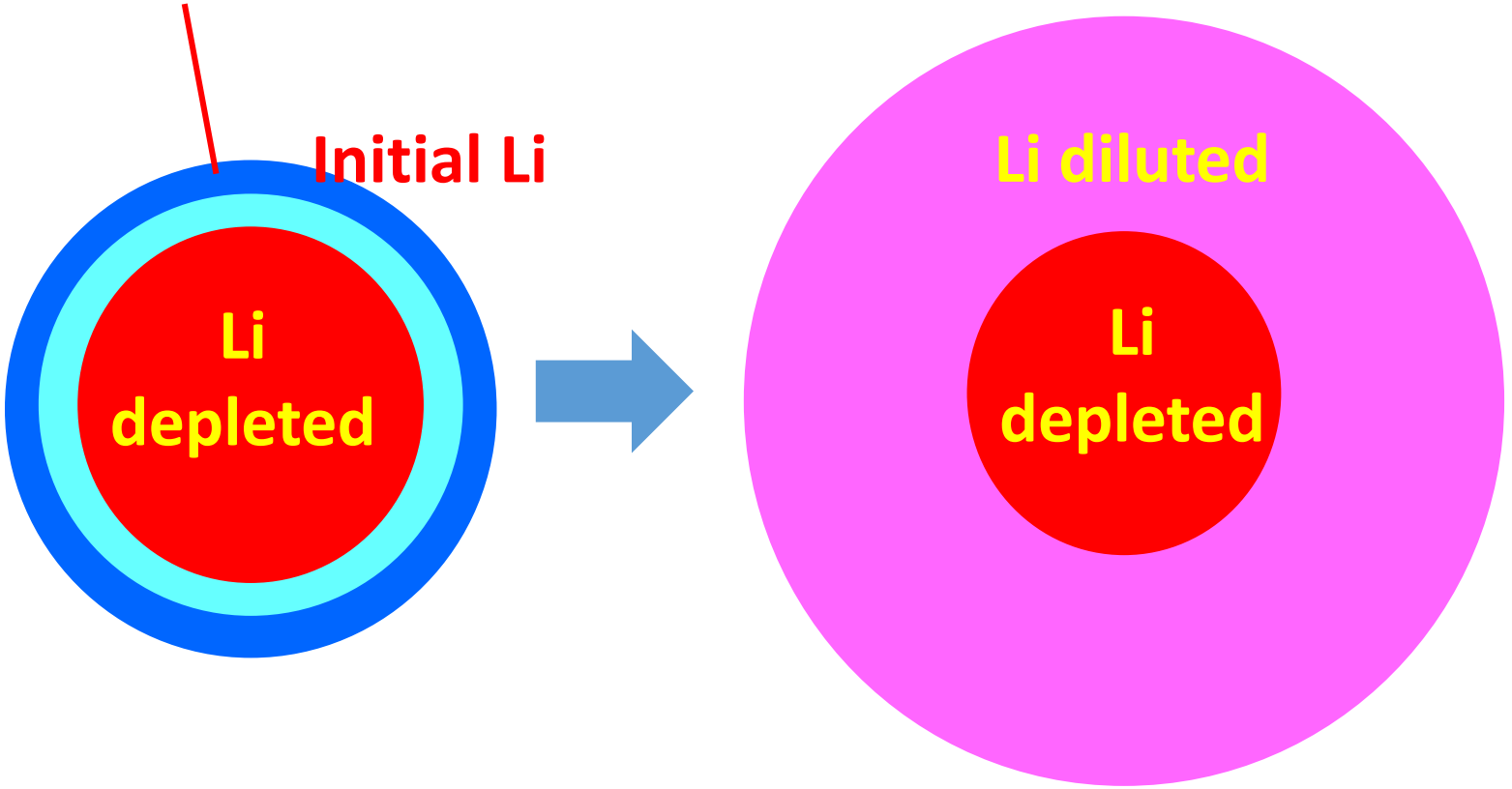
Li-enhanced very metal-poor stars

Main-sequence

shallow convective layer preserving initial Li abundance

Red giants

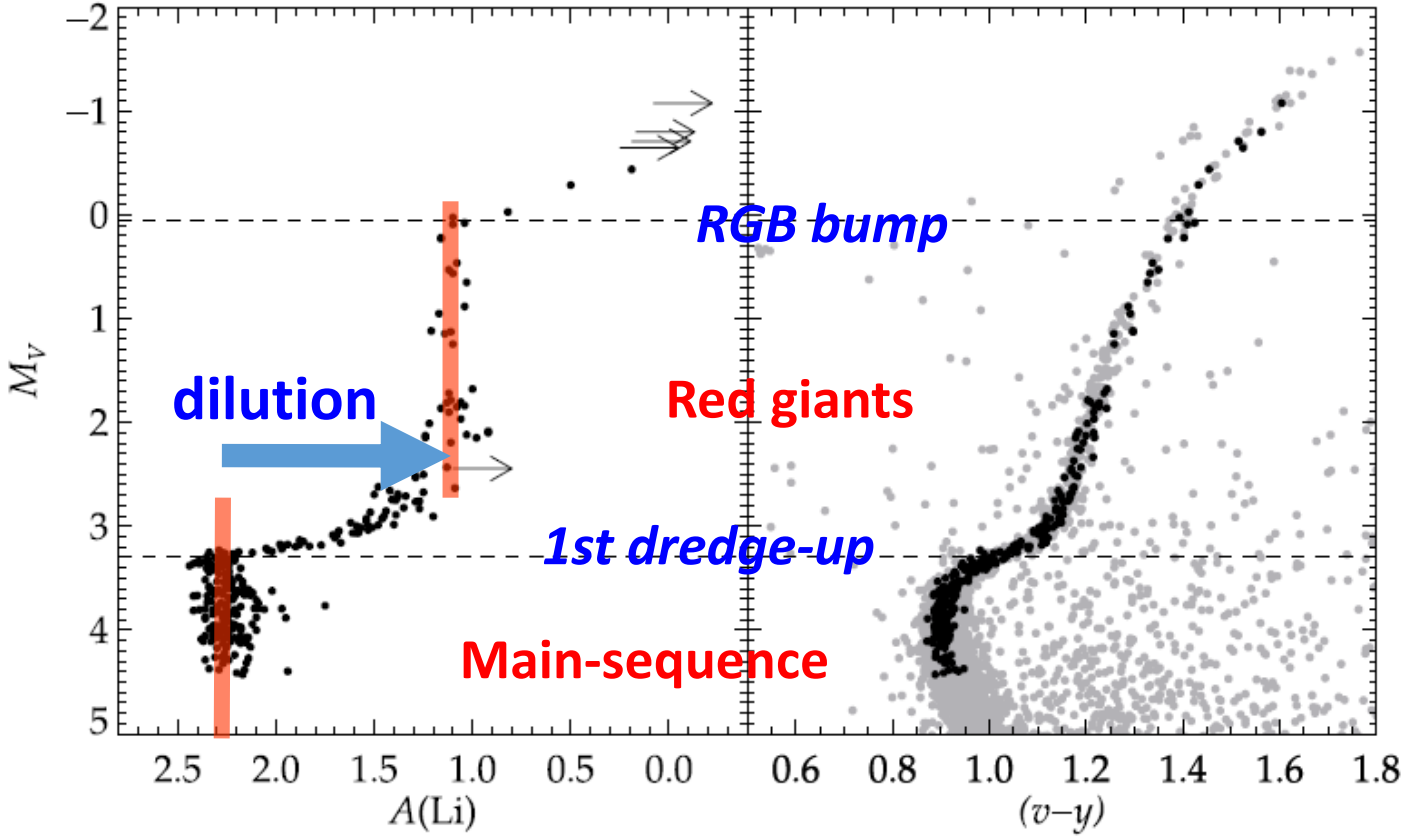
Surface Li diluted by the internal material due to *1st dredge-up*



Li abundances along low-mass star evolution traced by globular cluster stars

Lind et al. (2009)

Li abundances in stars of globular cluster NGC6397 ([Fe/H]=-2.0)

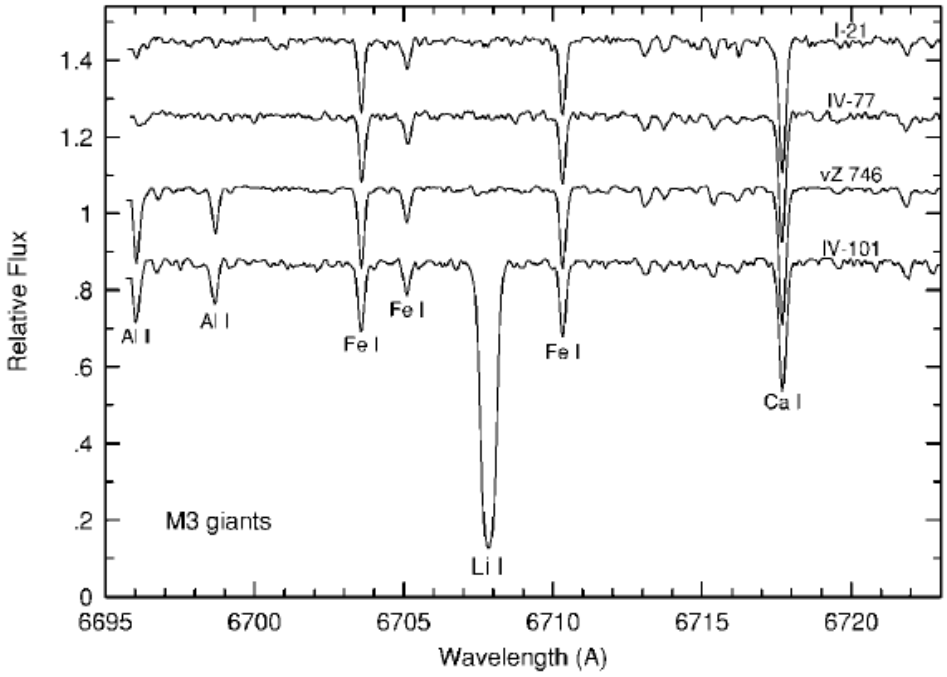


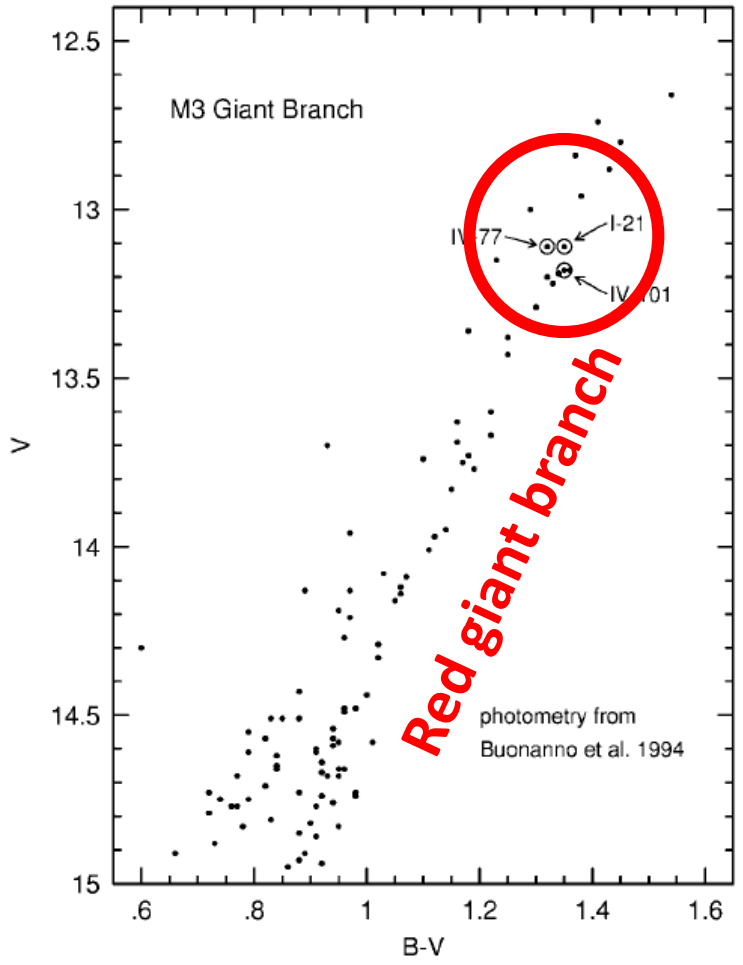
Red Giant Branch (RGB) bump*: evolutionary stage at which H-burning shell extends to the bottom of the layer mixed by the *1st dredge-up

Li-enhanced low-mass stars: Rare cases, but significant excess

- Kraft et al. (1999): a giant in the globular cluster M3
- Roederer et al. (2008): a field red giant

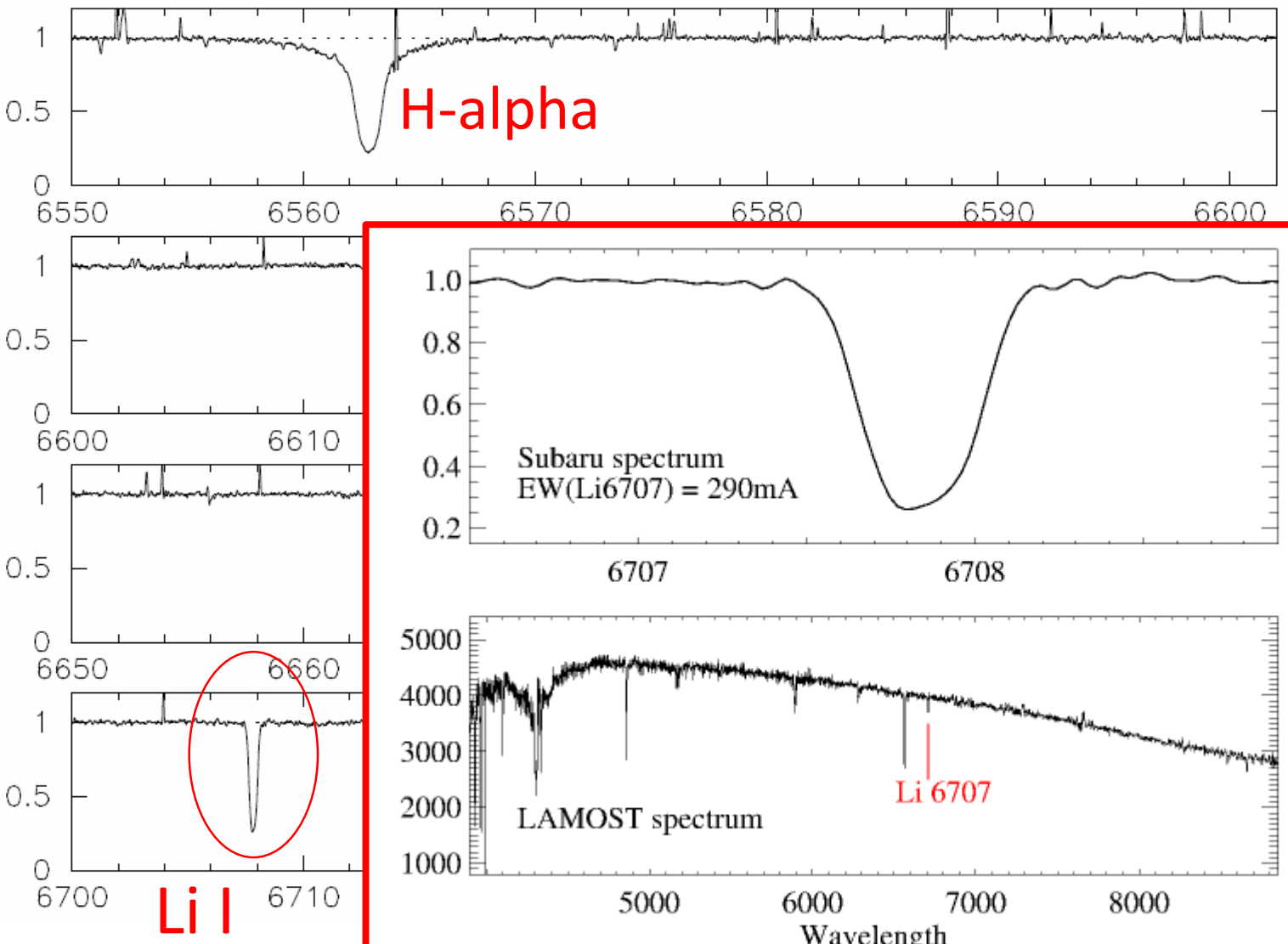
Kraft et al. (1999)





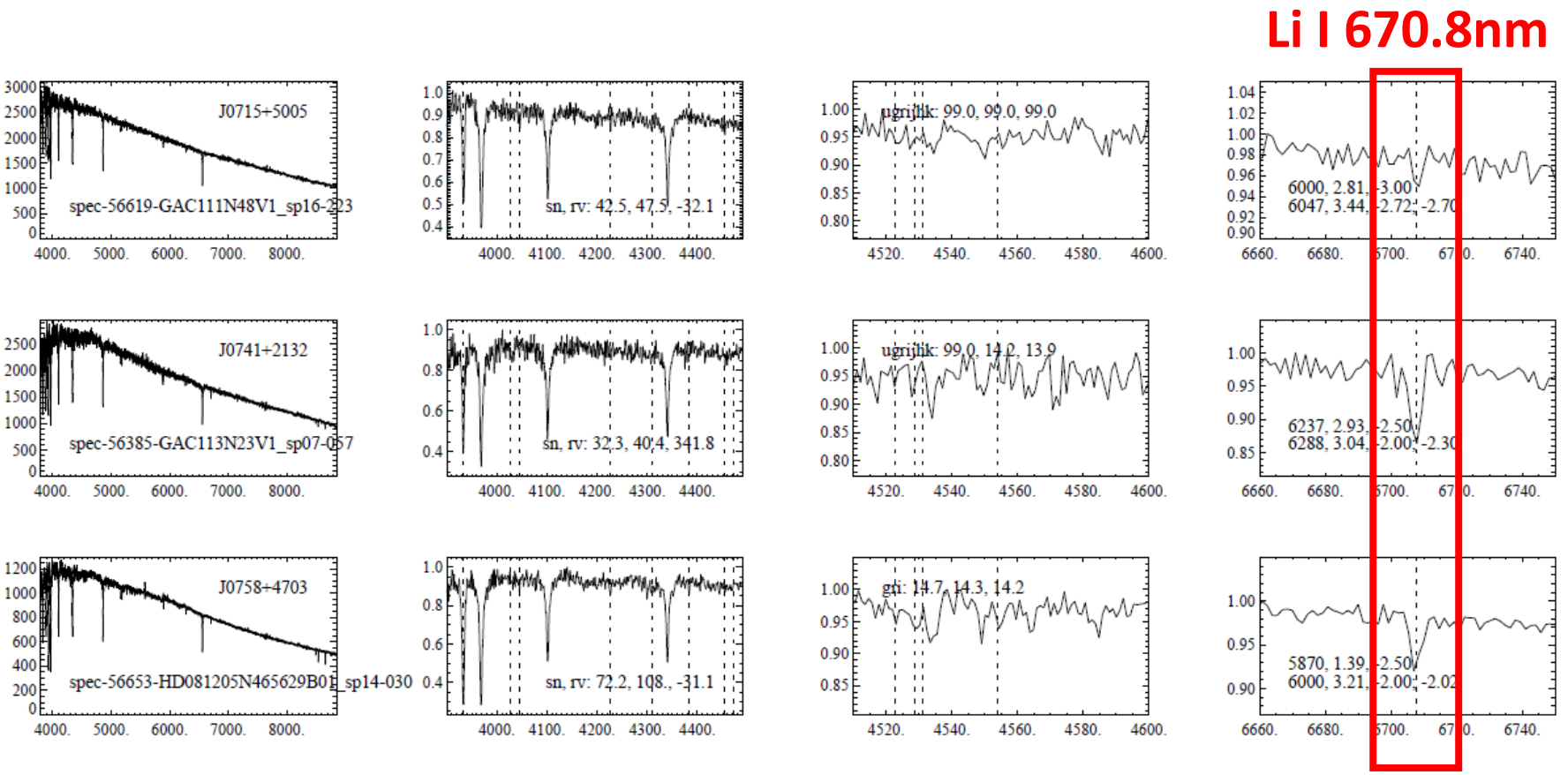
Super Li-rich red giant!

[Fe/H]=-3.3, T_{eff}=5200K, log g=2.2, A(Li)∼3.0



Target selection by LAMOST spectroscopy

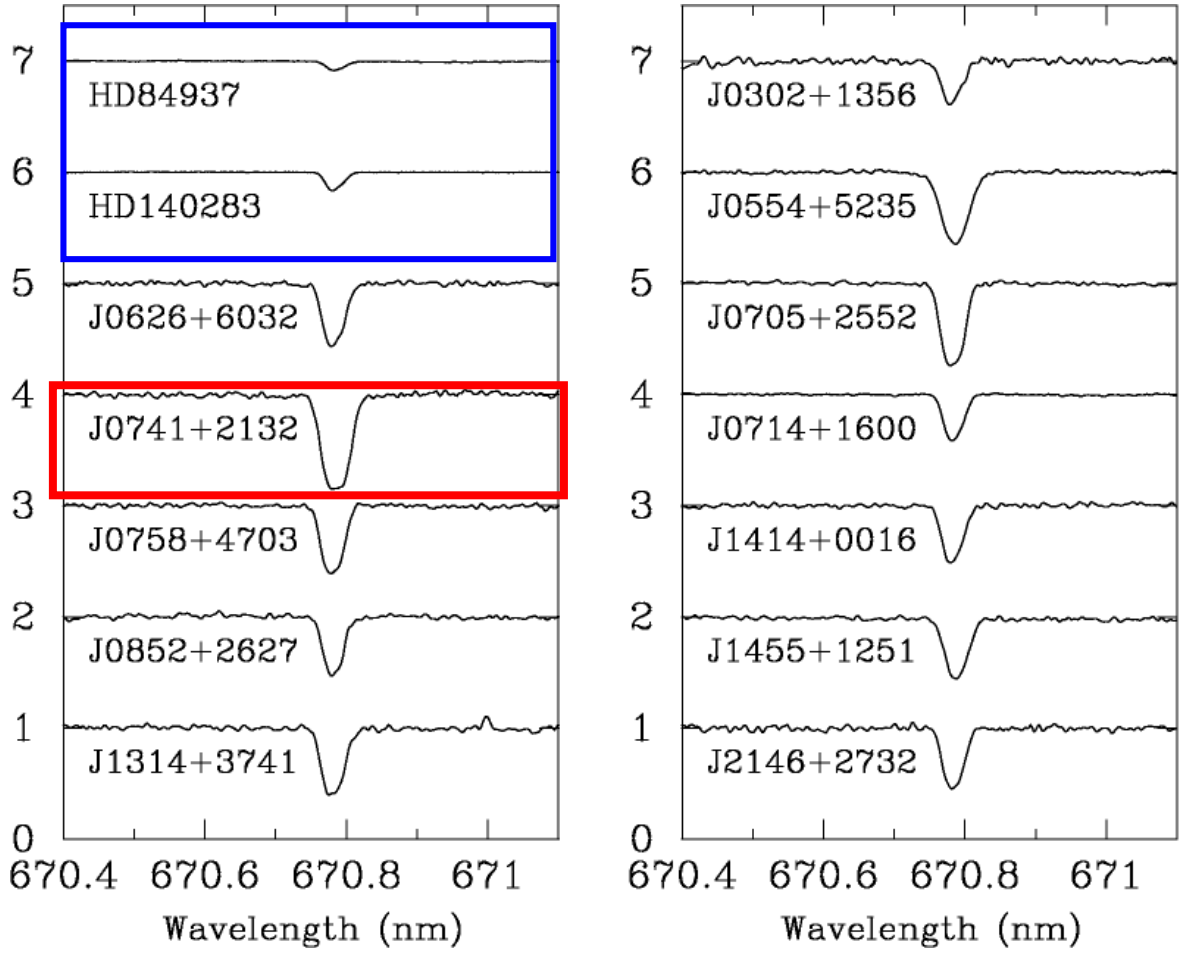
- ～1000 candidates for very metal-poor stars by pipeline analysis
- ～30 Li-rich star candidates by visual inspection



Subaru/HDS high-resolution spectra

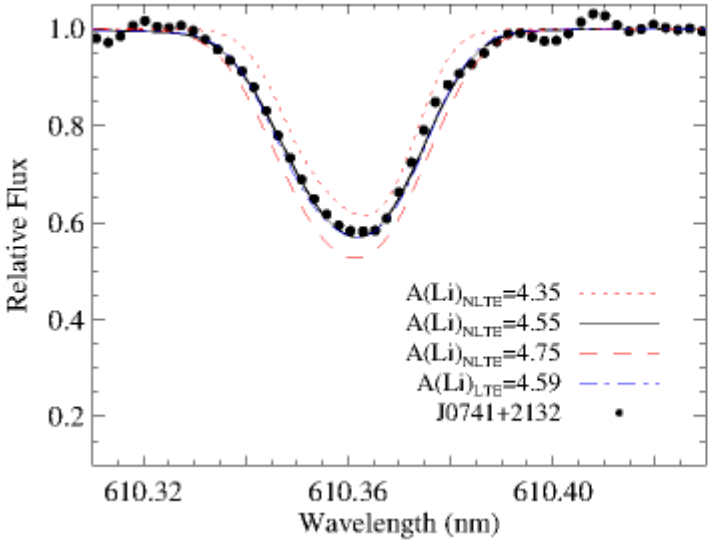
12 objects are identified with LAMOST/Subaru to be Li-rich with low metallicity ([Fe/H]<-1.7)

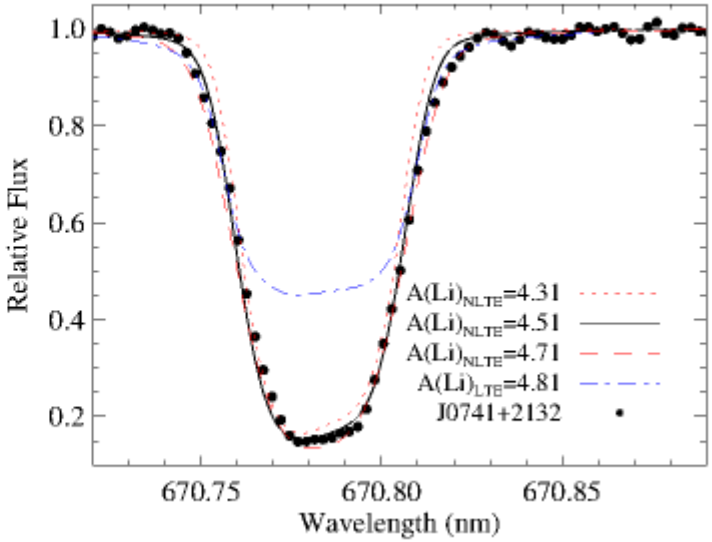
Comparison stars with normal Li



Abundance measurements from the two Li lines

The Li resonance line at 670.8nm is severely saturated in many cases. In such cases, the Li abundance is determined from the subordinate line at 610.36nm

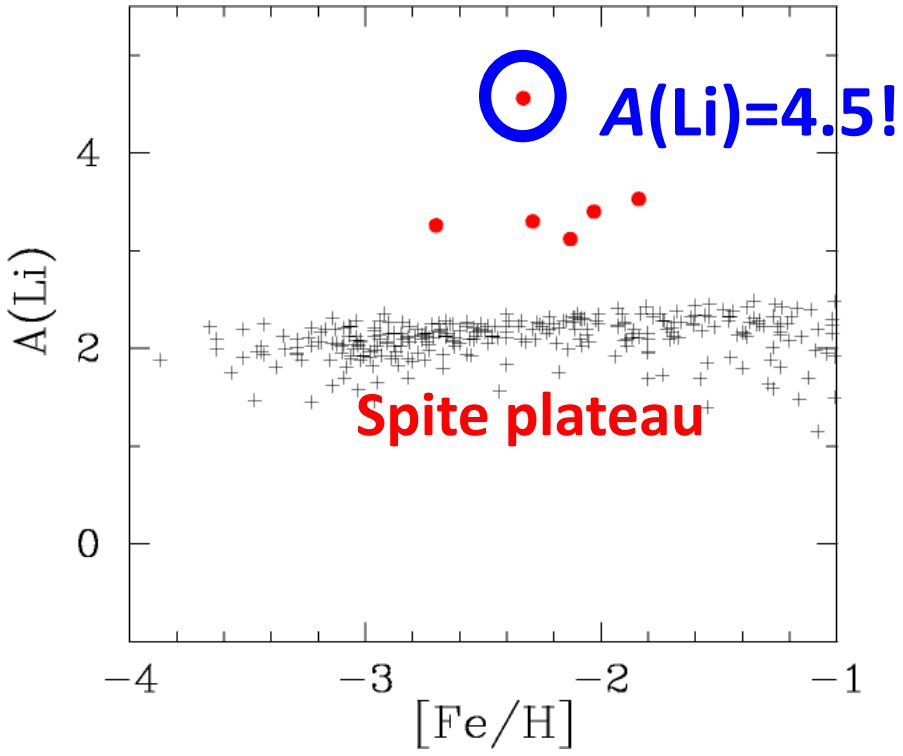




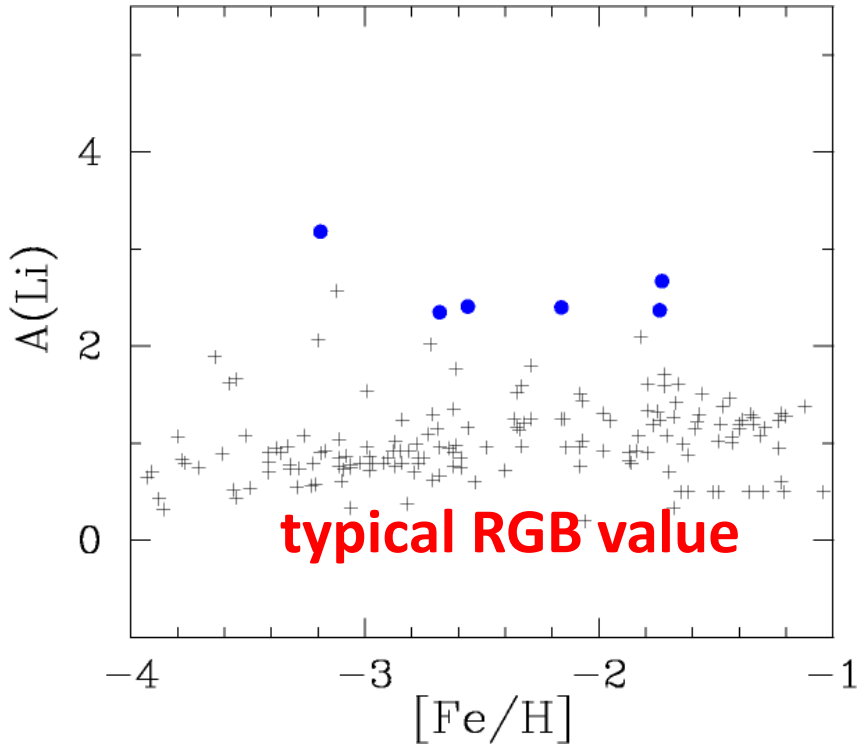
※ **Spectral features show asymmetry because the lines are doublet**

Li abundances as a function of [Fe/H]

Warm (unevolved) objects
(T_{eff}>5500K)
Li-rich = *A*(Li)>3



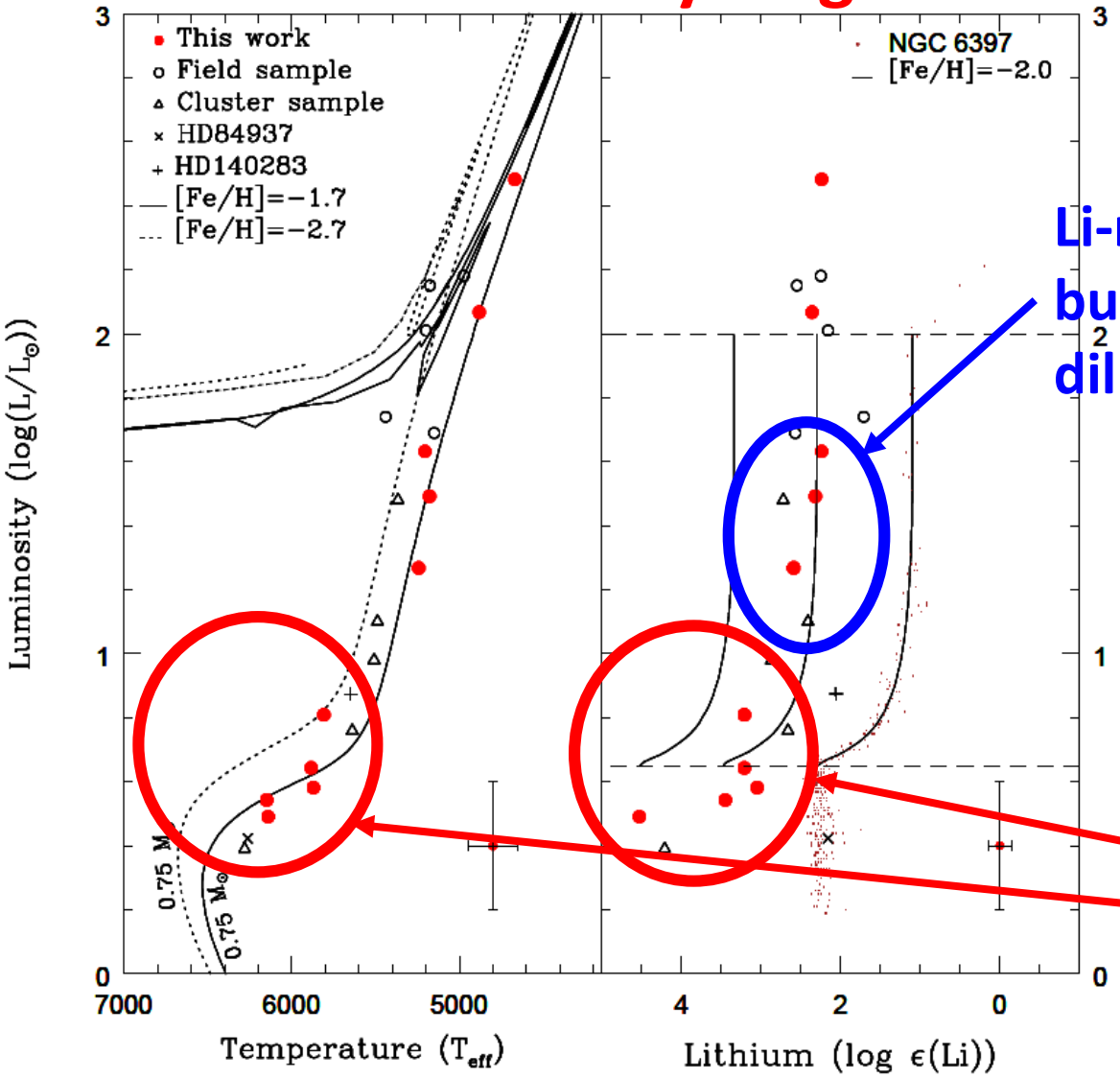
Red giants
(T_{eff}<5500K)
Li-rich = *A*(Li)>2



+ SAGA database

Observational result on Li-rich very metal-poor stars

2. Stellar evolutionary stage



Li-rich giants (before RGB bump) are explained by dilution by 1st dredge-up

Discovery of super Li-rich subgiants

Lithium-rich very metal-poor stars discovered with LAMOST and Subaru Summary

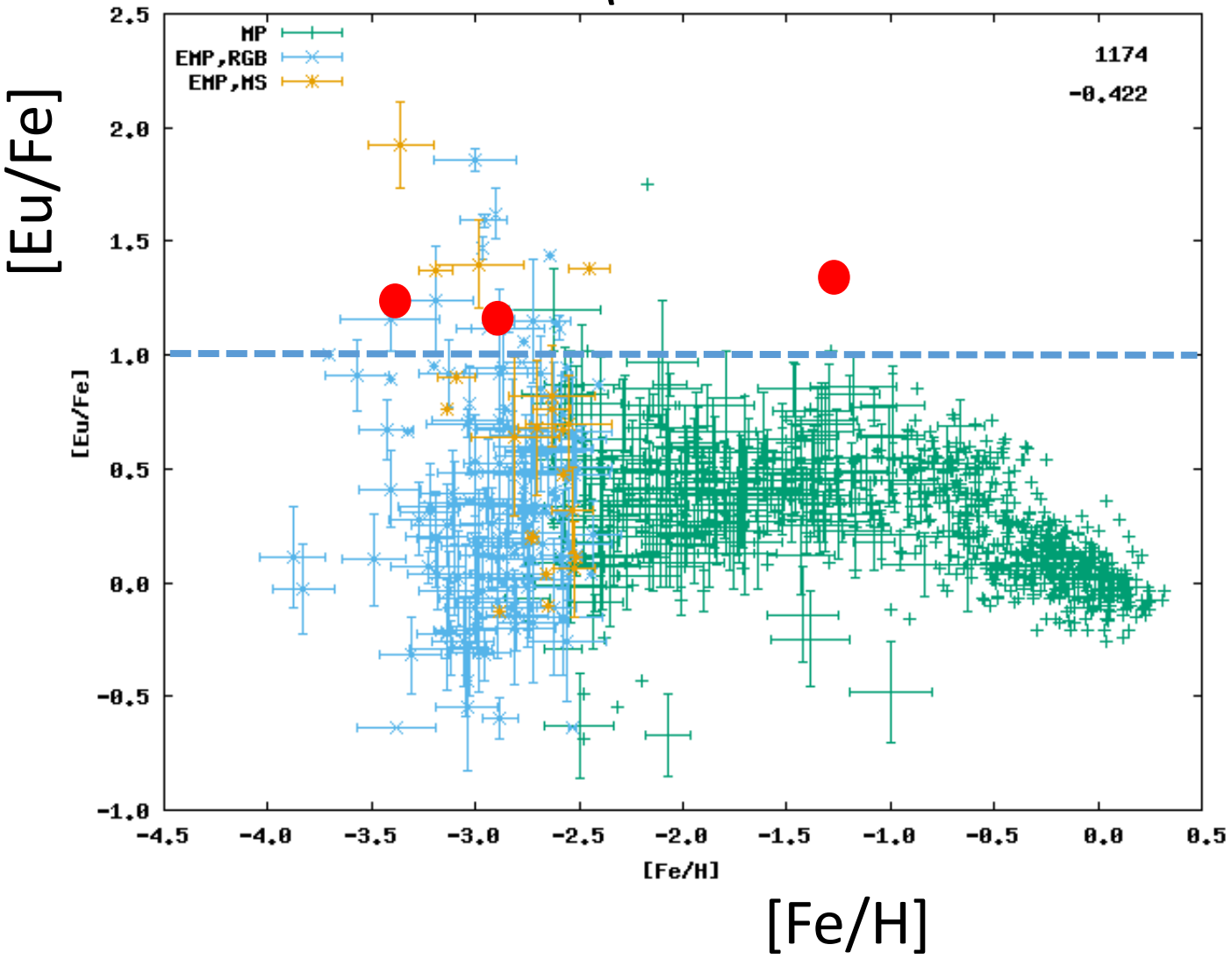
- **12 new Li-rich very metal-poor stars are discovered, among which 5 are warm subgiants before evolving to red giants.**
- **Assuming very high Li abundances (A(Li)>4) as initial values, as found in one of the subgiants in our sample, the (less significant) Li-excess in red giants is explained by dilution by 1st dredge-up.**
- **The focus is to search for the mechanism to make *extreme* Li-excess in stars *before evolving into red giants*.**

There is a mystery in low-mass star evolution even before the star evolves into a red giant.

New r-process enhanced (r-II) stars

New r-process enhanced (r-II) stars

SAGA database (Suda et al. 2008; 2017)
(Carbon-enhanced stars are excluded)

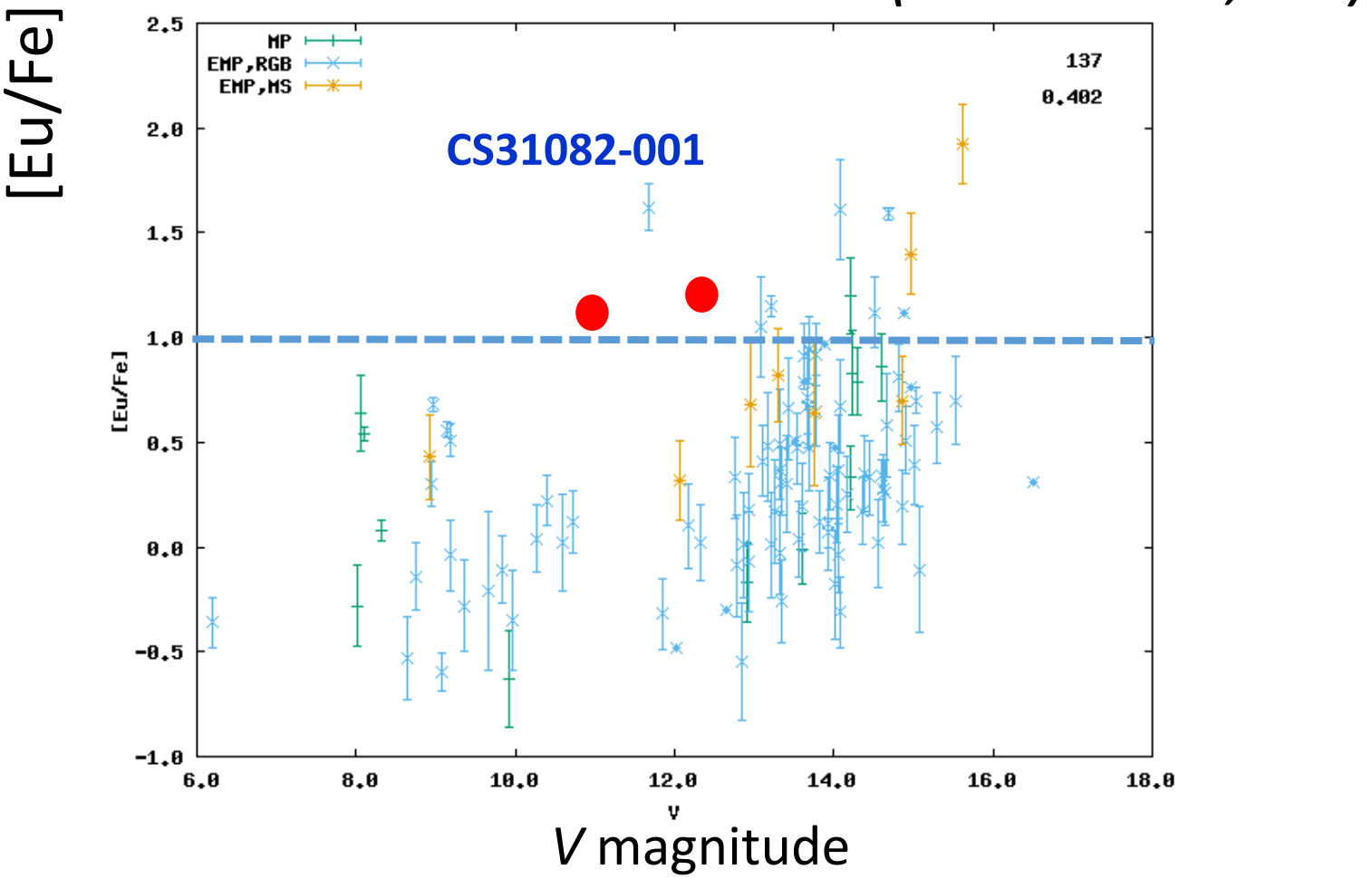


New r-process enhanced (r-II) stars

Bright r-II stars!

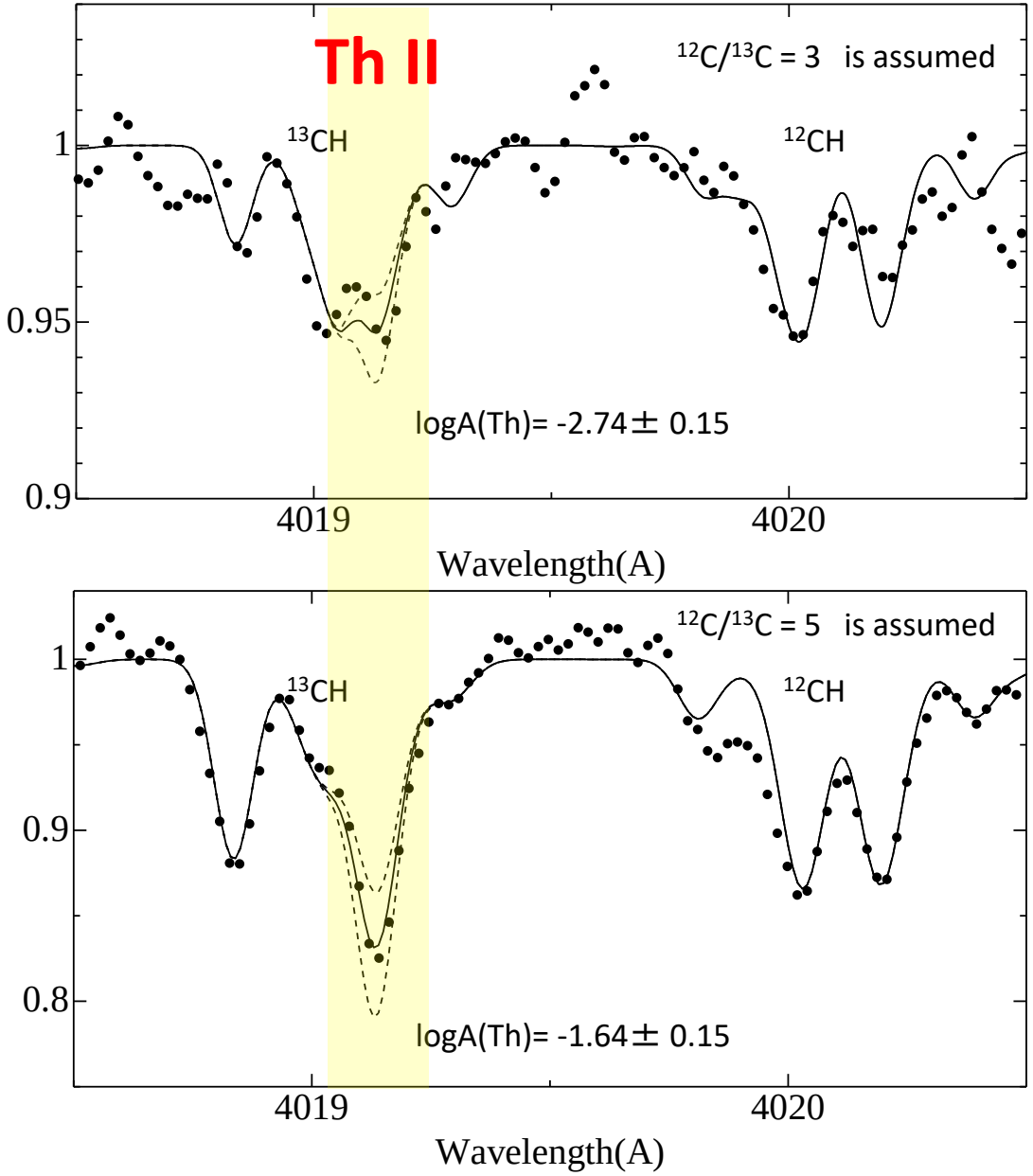
Stars with [Fe/H]<-2.5

SAGA database (Suda et al. 2008; 2017)



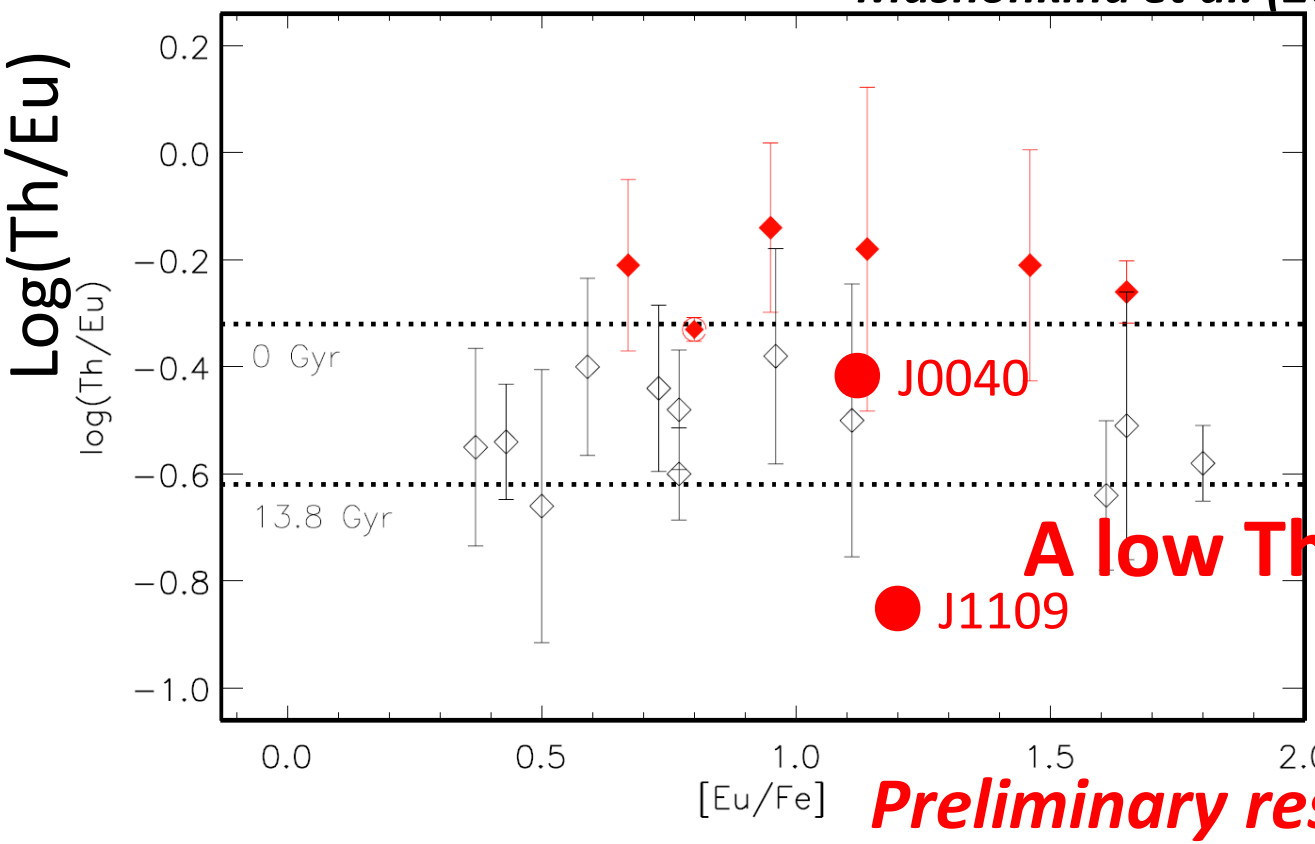
New r-process enhanced (r-II) stars

Detection of Th in r-II stars with low metallicity



Th/Eu abundance ratios: small scatter with some "actinide-boost" stars

Mashonkina et al. (2014)



A low Th/Eu star!?

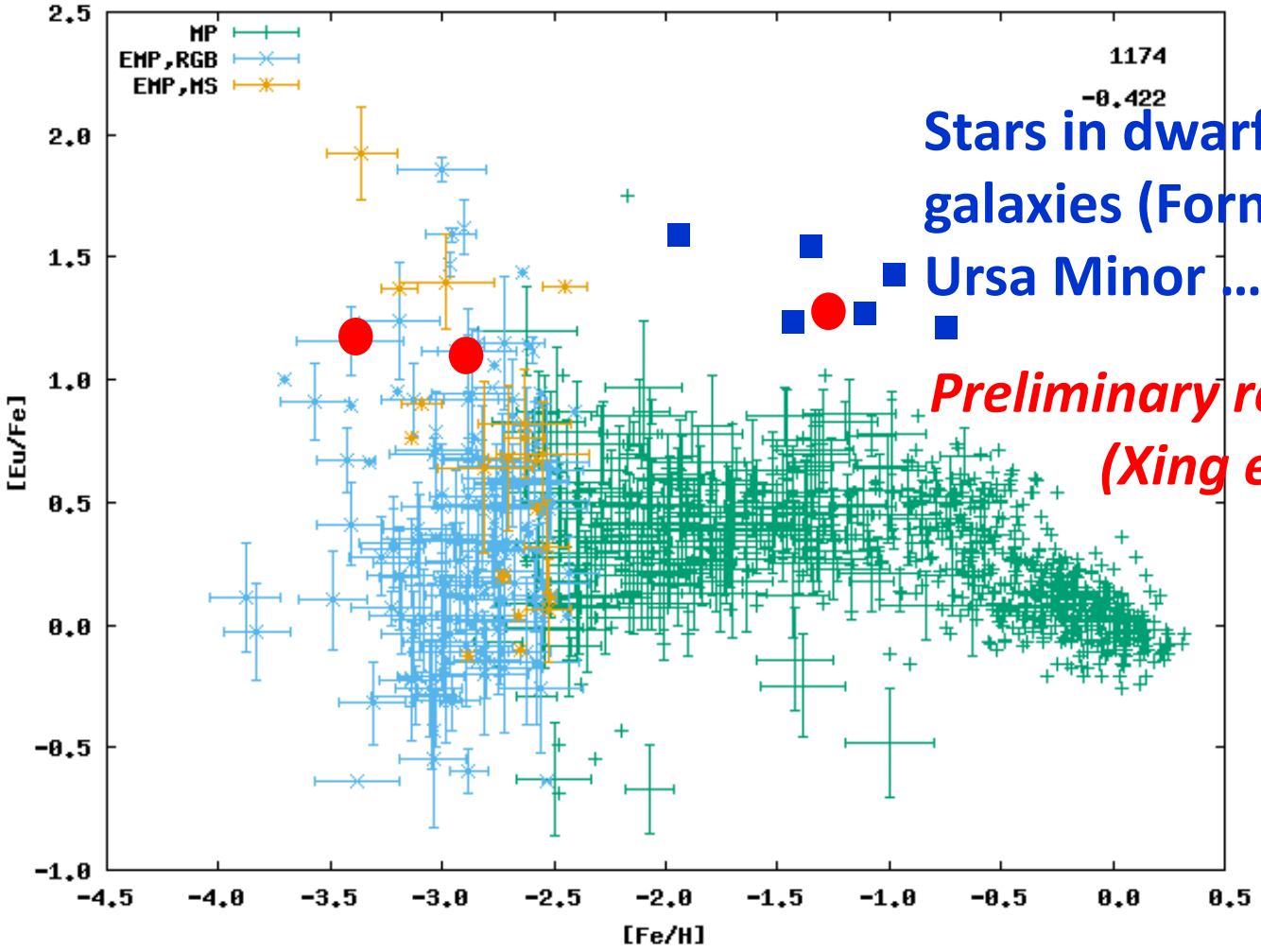
Preliminary result (Honda et al.)

[Eu/Fe]

New r-process enhanced (r-II) stars

Metal-rich r-II star !

Strong evidence of late accretion of a classical dwarf galaxy-like object!



Stars in dwarf galaxies (Fornax, Ursa Minor …)

Preliminary result (Xing et al.)

Publications and plans

- Published
  - Aoki et al. (2017, PASJ) Post-AGB sta J1833+3138= CC Lyr
  - Li et al. (2018, ApJL) Li-enhanced very metal-poor stars
- 1st Draft ready
  - Li et al., Li-enhanced extremely metal-poor star J0705
  - Xing et al., alpha-poor/r-process-rich star
  - Zhao et al., moving group stars I
  - Aoki et al., alpha-rich CEMP star J2217
  - Liang et al., moving group stars II
- Draft in preparation
  - Honda et al., r-process-rich extremely metal-poor stars
  - Zhang et al., CEMP turn-off stars
- Main sample: Aoki, Li, Matsuno et al.

  -project summary + binary frequency

  -abundance results

  -combination with Gaia

Summary and future prospect

LAMOST is providing huge samples of metal-poor stars and other chemically/kinematically interesting objects. We are conducting follow-up spectroscopy with Subaru for 500 stars.

- **LAMOST objects studied with Subaru are relatively bright, providing good sample for detailed abundance studies.**
- **Observing program is very successful**
- **Publications for various topics are ongoing**
- **Combining kinematics data provided by Gaia**