Evidence for the accretion origin of halo stars with an extreme r-process enhancement

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Outline

1) **alpha-elements in dwarf spheroidal galaxies and the Galactic halo**

   >alpha-poor metal-poor stars in the Galactic halo

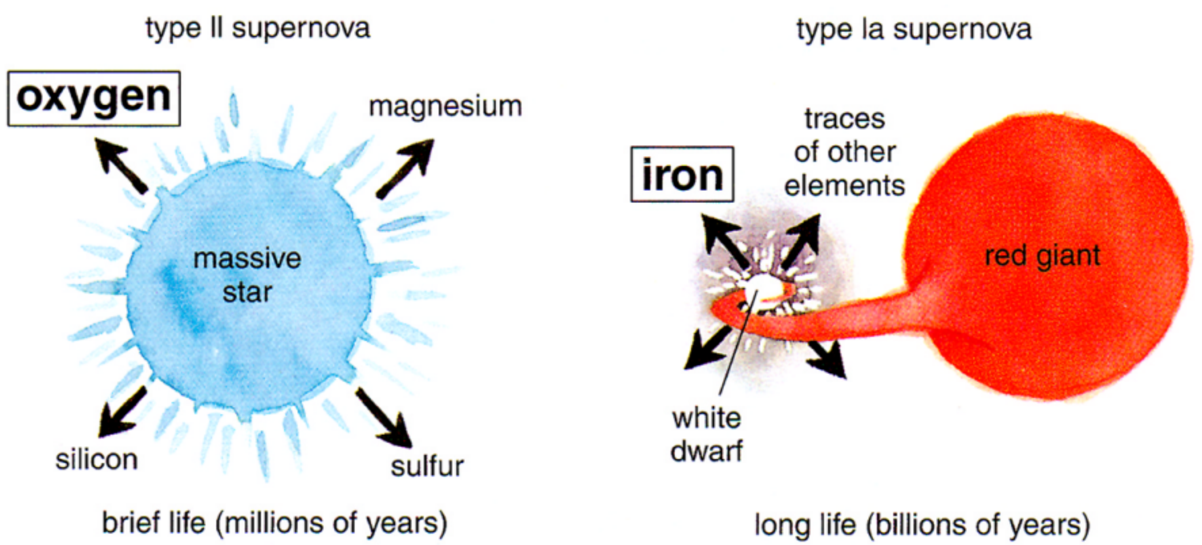
2) **LAMOST-Subaru collaboration**

   > a search for alpha-poor metal-poor stars

3) **A newly discovered alpha-poor star with an extreme r-process enhancement**

   >evidence for a later accretion of a dwarf galaxy

α-elements in dwarf spheroidal galaxies and the Galactic halo



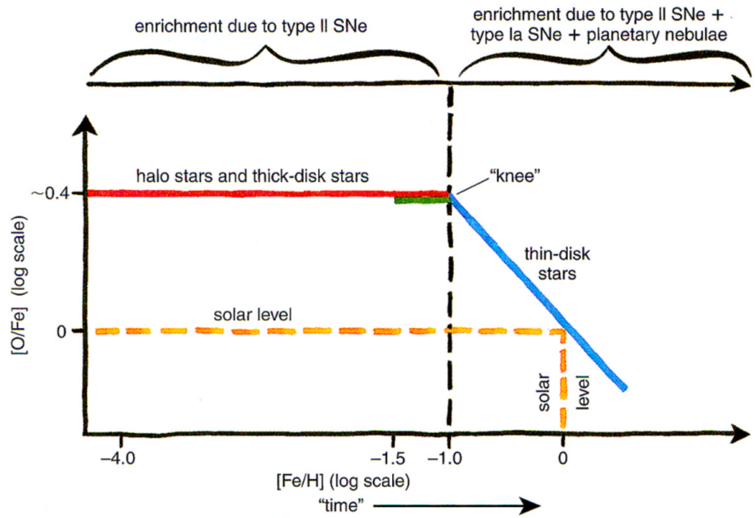
Time delay

Element-building occurs mainly via supernova explosions: exploding stars return chemically enriched gas to the interstellar gas - then new stars form.

The alpha elements (Mg, Ca, Si, Ti) come mainly from massive supernovae: stars with masses > 8 $M_\odot$ which explode within a few million years

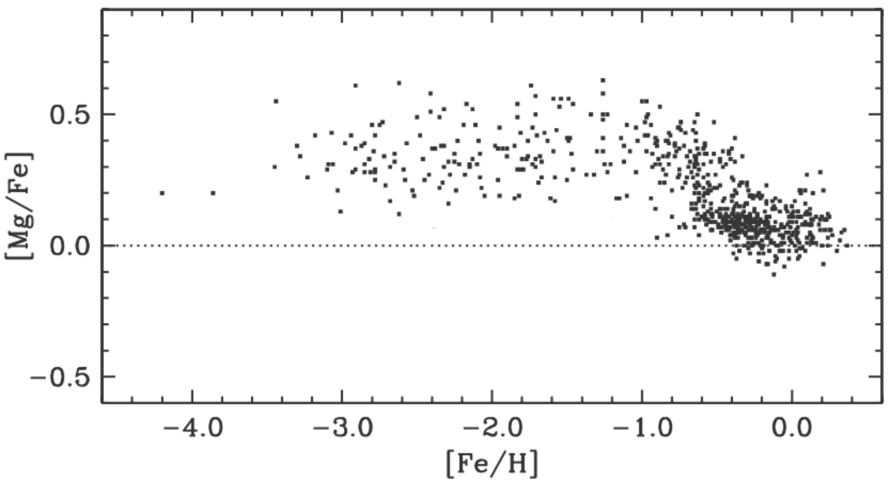
Fe comes mainly from low mass supernovae which take 1-2 Gyr to explode

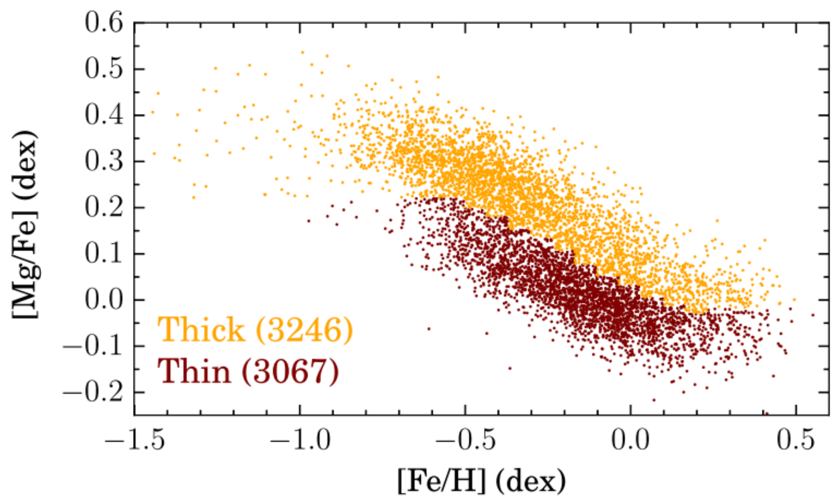
alpha/Fe in the Milky Way



The general trend of
[α/Fe]-[Fe/H] in the Milky Way.

$[A/B] \equiv \log_{10}(N_A/N_B)_\star - \log_{10}(N_A/N_B)_\odot$ and $\log \epsilon(A) \equiv \log_{10}(N_A/N_H) + 12.00$ for elements A and B.





[Mg/Fe] vs. [Fe/H] in stars in the halo, thick and thin disks:

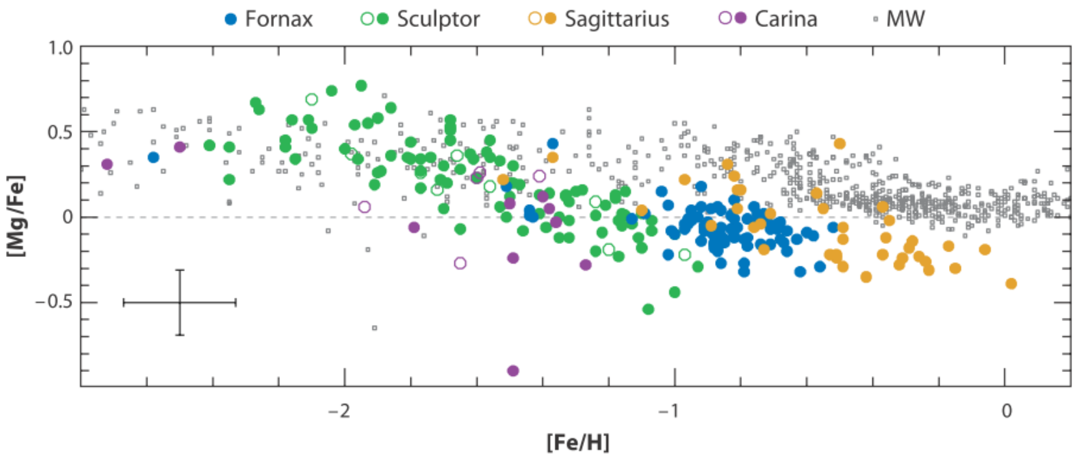
Roederer 2009, Gaia-ESO data from Rojas-Arriagada et al. 2017

alpha/Fe in MW's satellite dwarf galaxies

- **MW's satellite galaxies: dwarf spheroidal (dSph) galaxies**

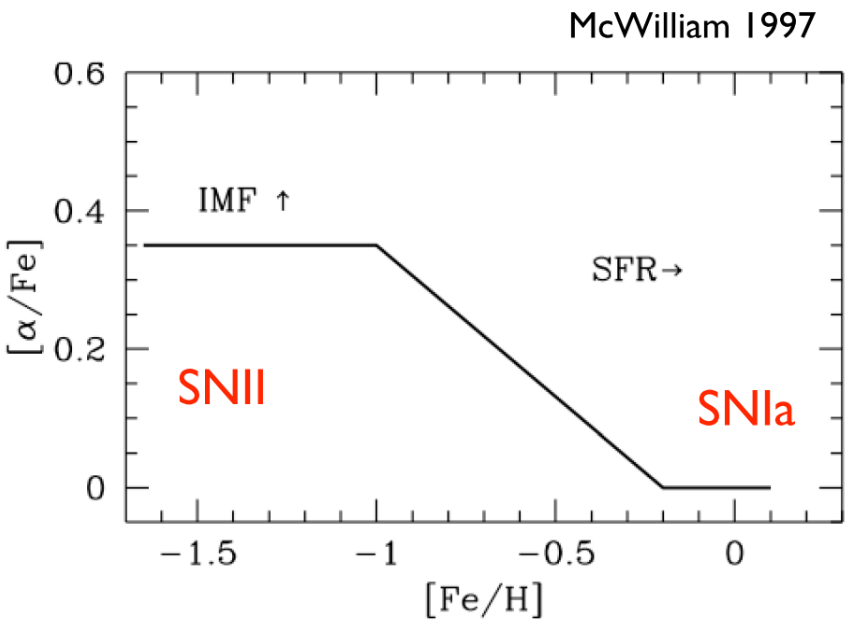
- **α-deficiencies in present-day dSphs(Tolstoy et al. 2009)**

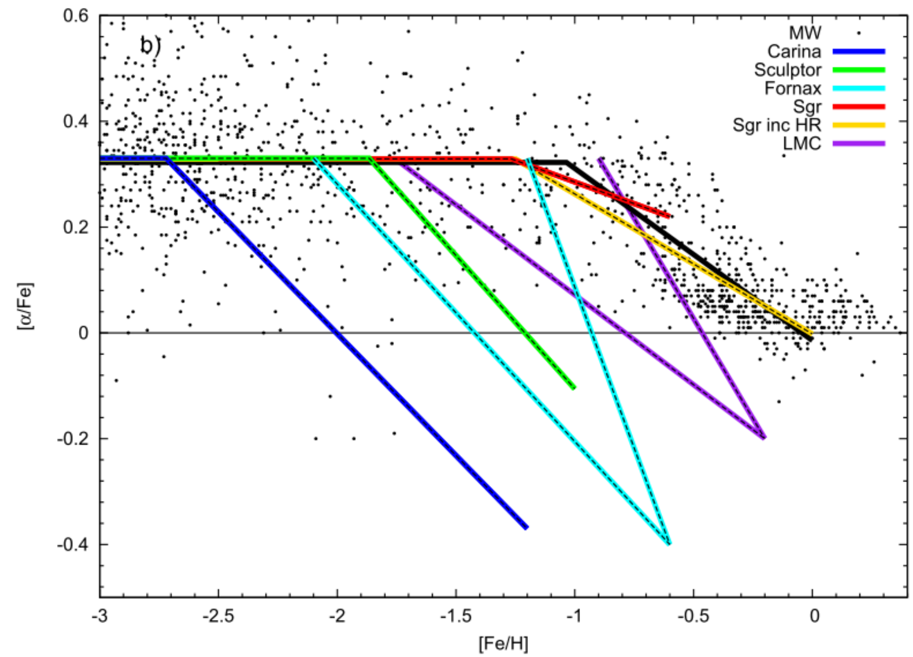
the true building blocks of the Galactic halo?



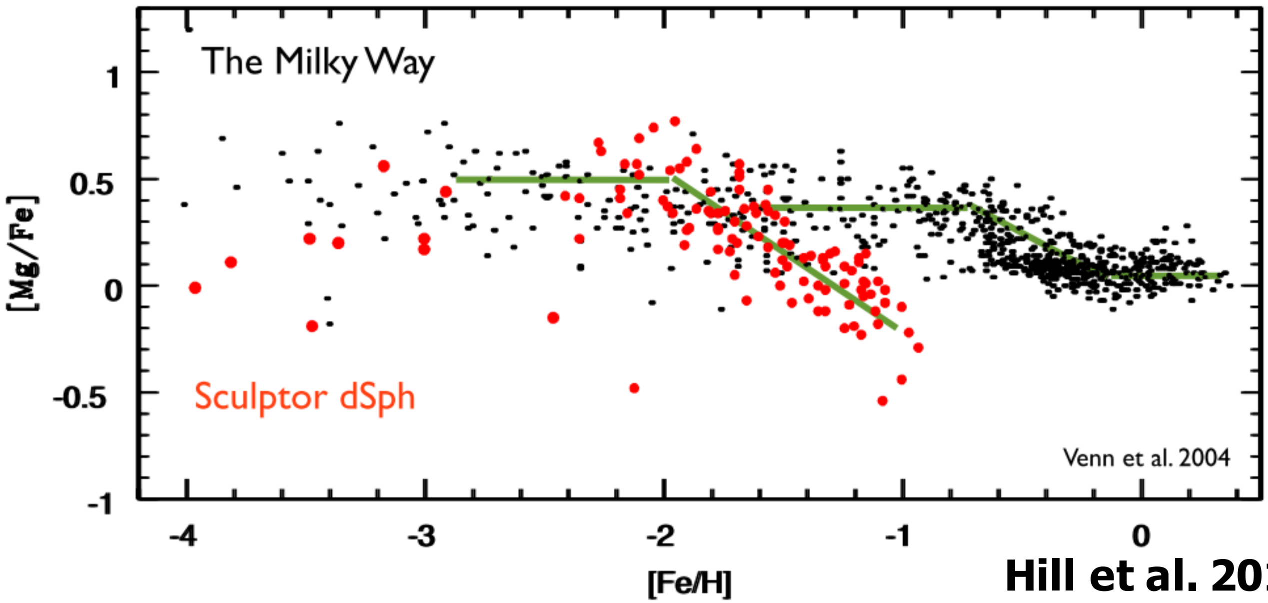
Tolstoy et al. 2009

alpha/Fe in MW's satellite dwarf galaxies





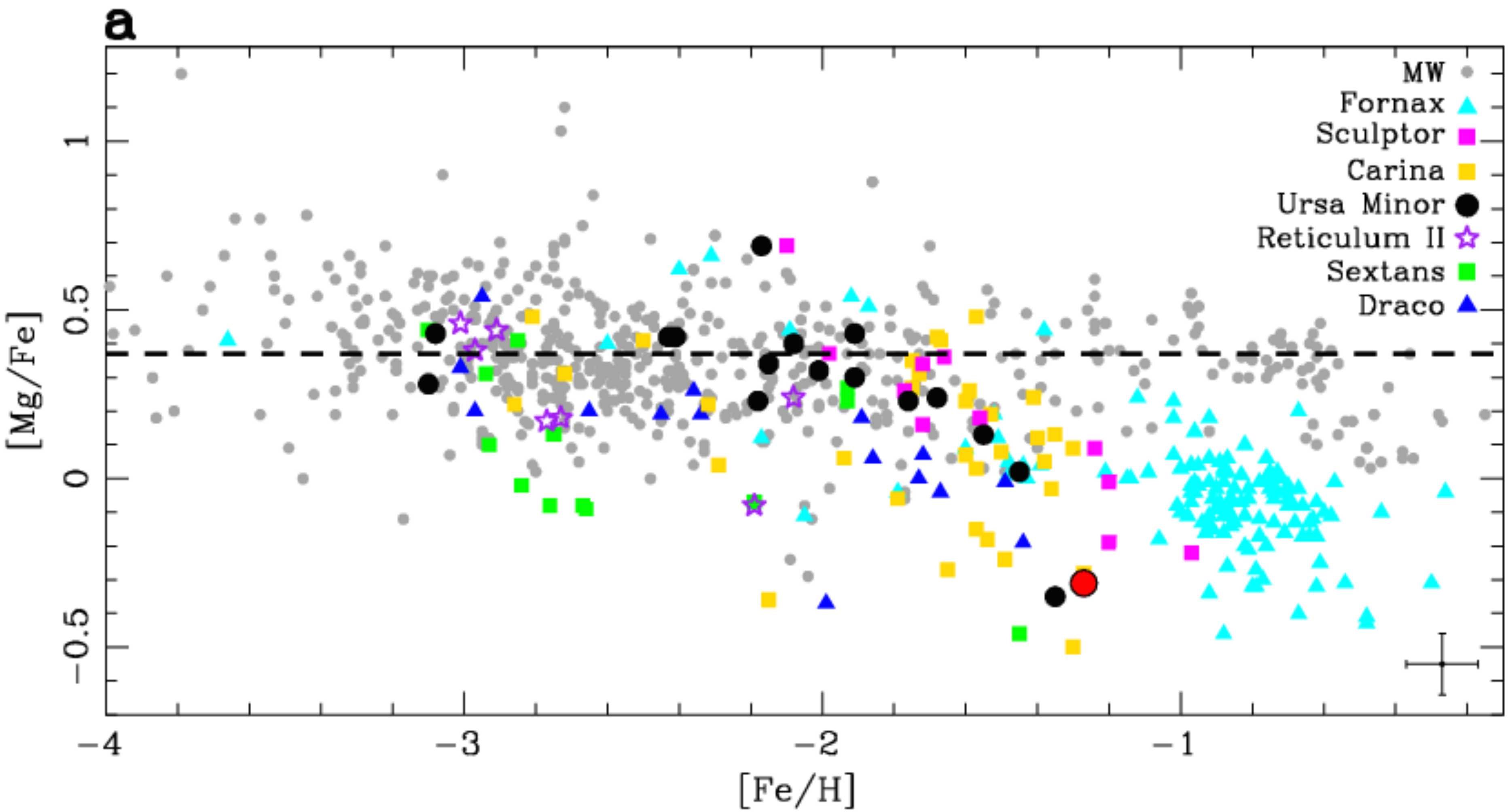
The knee



Hill et al. 2018

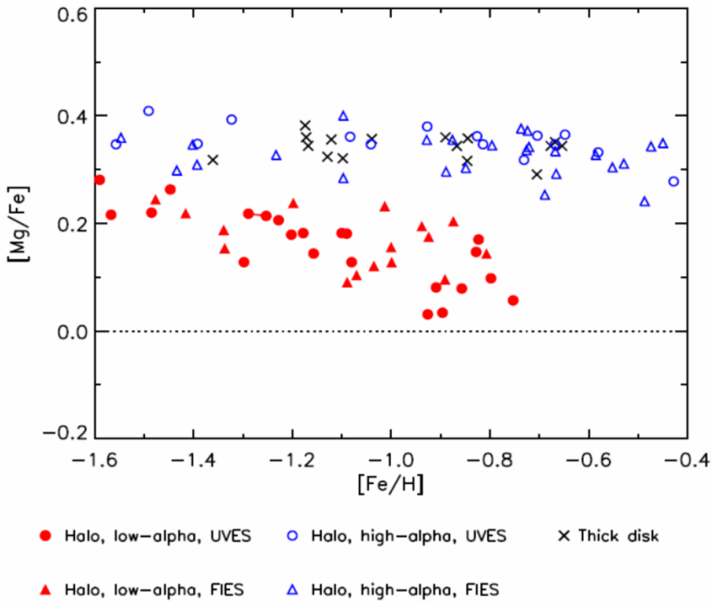
alpha/Fe in MW's satellite dwarf galaxies

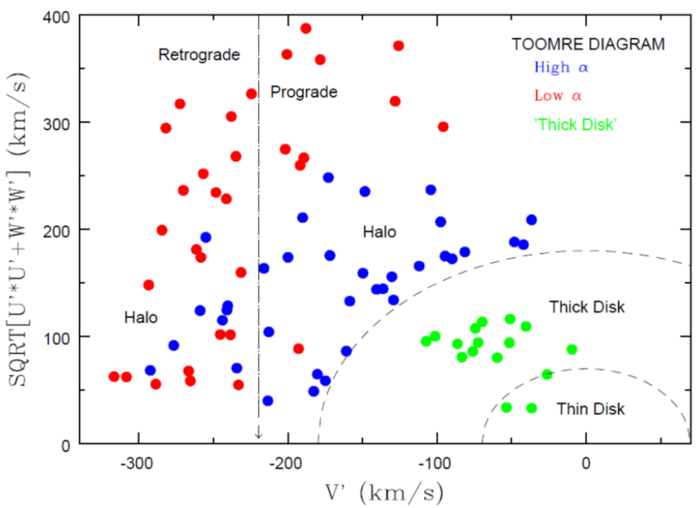
- **Alpha-poor metal-poor stars in dwarf galaxies**



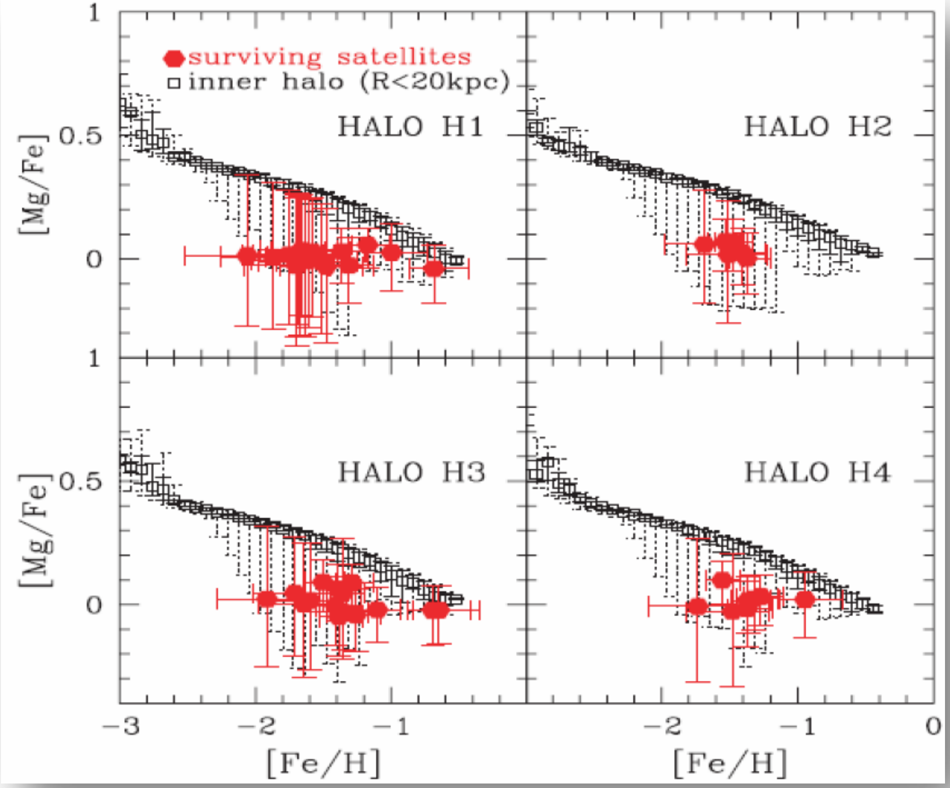
Xing et al. 2019

Link dSphs with MW's Halo: low alpha/Fe halo stars





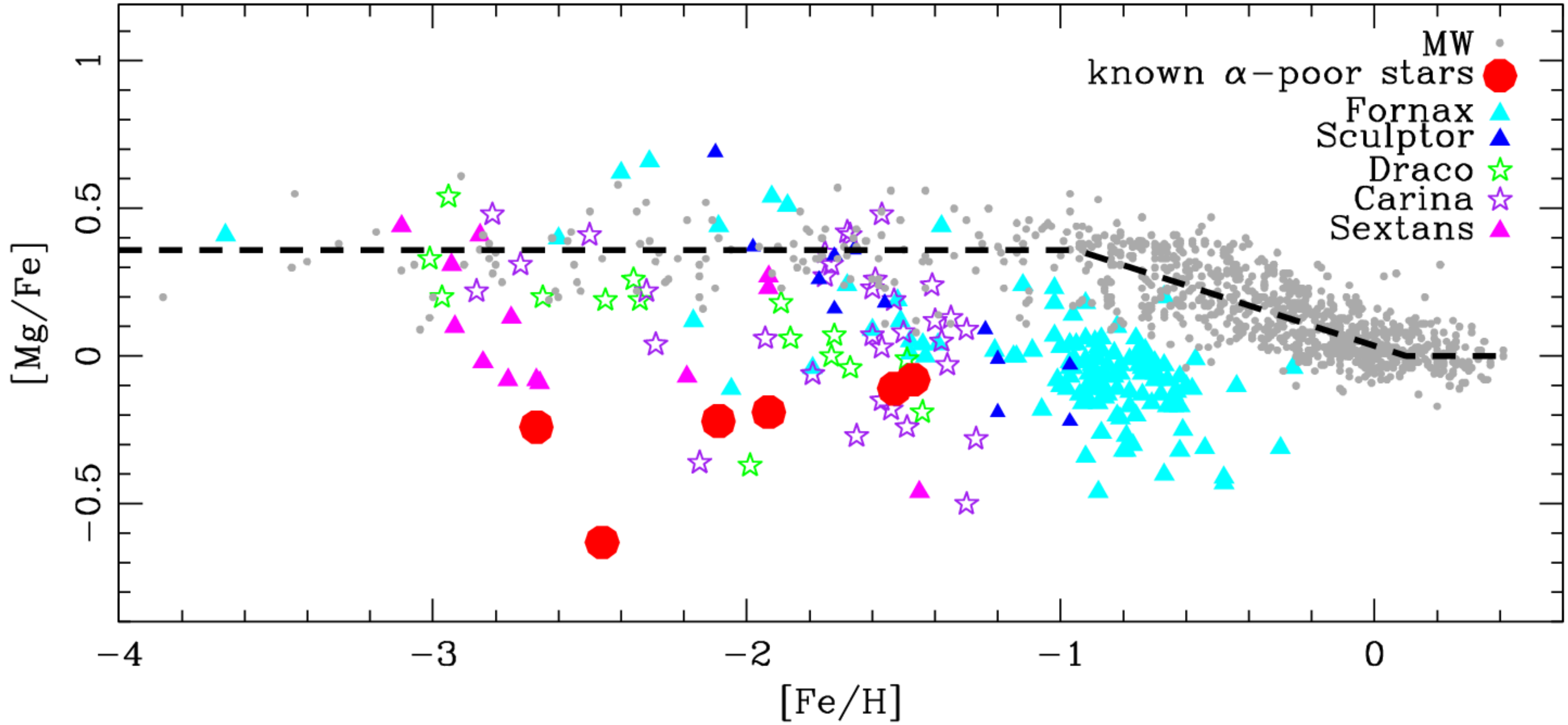
Low-alpha halo stars: Nissen 2010



Font, Johnston, Bullock & Robertson, 2006: "Chemical abundance distributions of Galactic halos and their satellite systems in a LambdaCDM Universe"

Link dSphs with MW's Halo

- **α-poor stars in the Galaxy**
  - **similar to stars in the dwarf galaxies**
  - **outer halo component: formed through a dissipationless chaotic merging of smaller subsystems(Carollo et al. 2007)**
  - **dSphs: surviving counterparts of such subsystems**
  - **α-poor halo stars: signatures of past merger events**



A search for alpha-poor metal-poor stars

LAMOST (郭守敬望远镜)

- LAMOST (The **L**arge Sky **A**rea **M**ulti-**O**bject Fibre **S**pectroscopic **T**elescope)
  - Commissioning: 2009.9 - 2011.5
  - Pilot survey: 2011.10 - 2012.5
  - Regular survey (Phase I): 2012.9 – 2017.6
  - Phase II: 2018.10 –
- Combination of large aperture (4m) and wide field (5deg)
- High spectra-obtaining efficiency: 3,400 targets at one exposure

LAMOST @ Xinglong, China

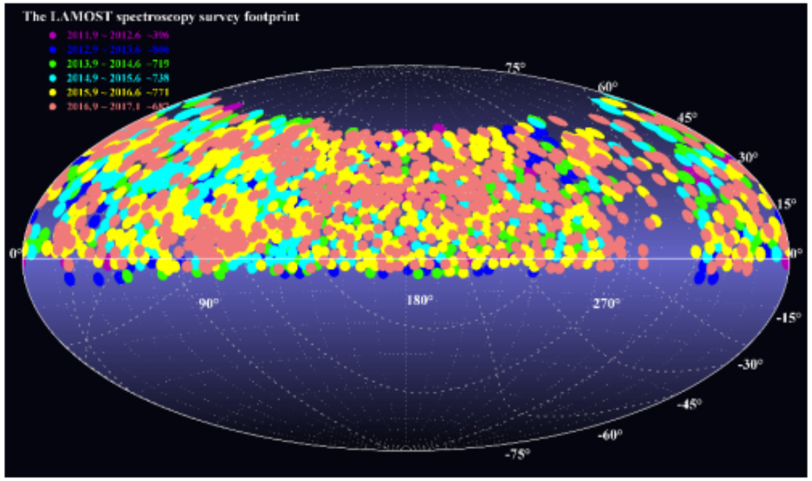
- **~4m**
- **4,000 fibers**
- **r ~17.8**
- **370nm – 900nm**

A search for alpha-poor metal-poor stars

LAMOST data releases

Large survey area
(North 7700 deg^2 + South 3500 deg^2)

> 1.5 million spectra / year



	Ending date	No. of spectra	No. of stellar spectra	Spectra of SNR > 10	No. of spectra with parameters	Release/Public date
DR0	20120617	958,944	812,911	619,151	396,249	2012.08/2012.08
DR1	20130603	2,660,613	2,342,849	1,925,735	1,127,872	2013.09/2015.03
DR2	20140603	4,309,098	3,843,851	3,293,600	2,174,812	2014.12/2016.07
DR3	20150602	5,968,162	5,354,883	4,665,075	3,185,475	2015.12/2017.07
DR4	20160602	7,681,185	7,682,298	6,076,210	4,202,127	2016.12/2018.07
DR5	20170608	9,017,844	8,171,443	7,531,398	5,344,058	2017.12/2019.07

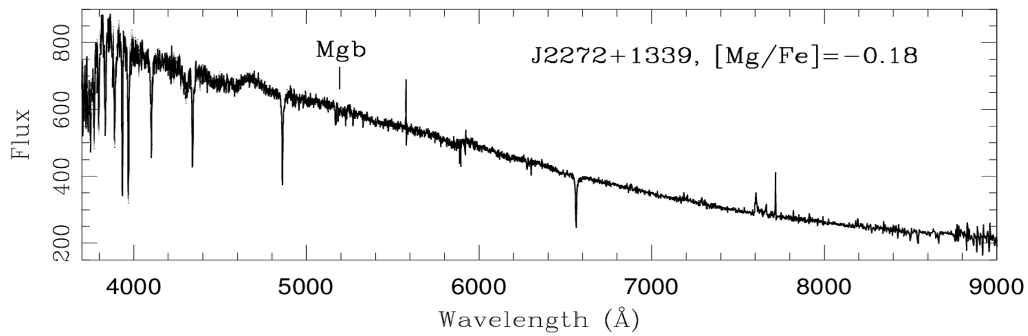
LAMOST provides a good opportunity to search for APMP stars in halo.

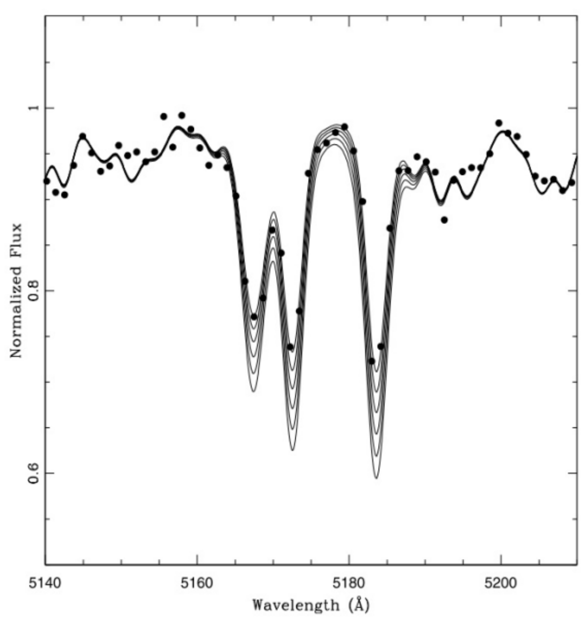
Searching for α-poor stars from LAMOST data

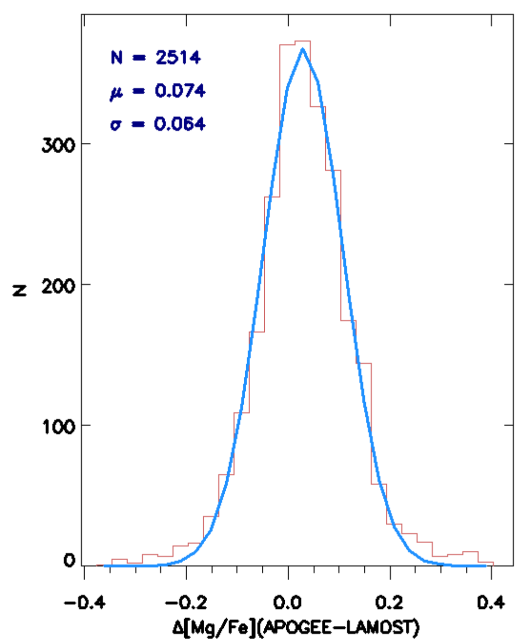
- Determination of [Mg/Fe] based on LAMOST data:

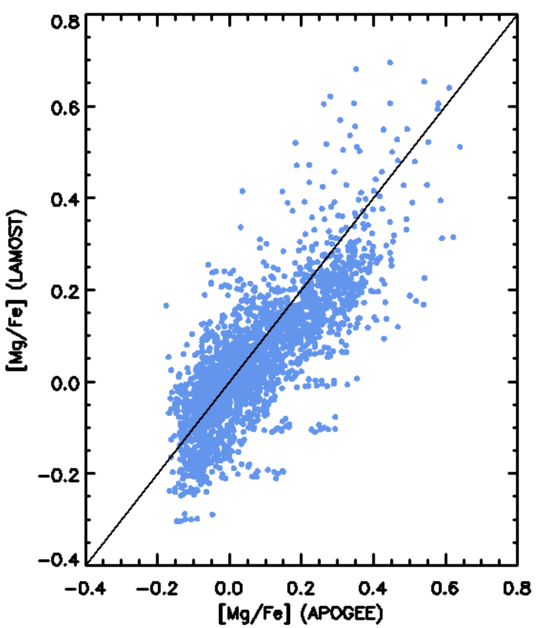
Xing et al. ApJ, 2014, 2015

- Typical uncertainty ~0.15 dex for spectra with SNR ~ 40



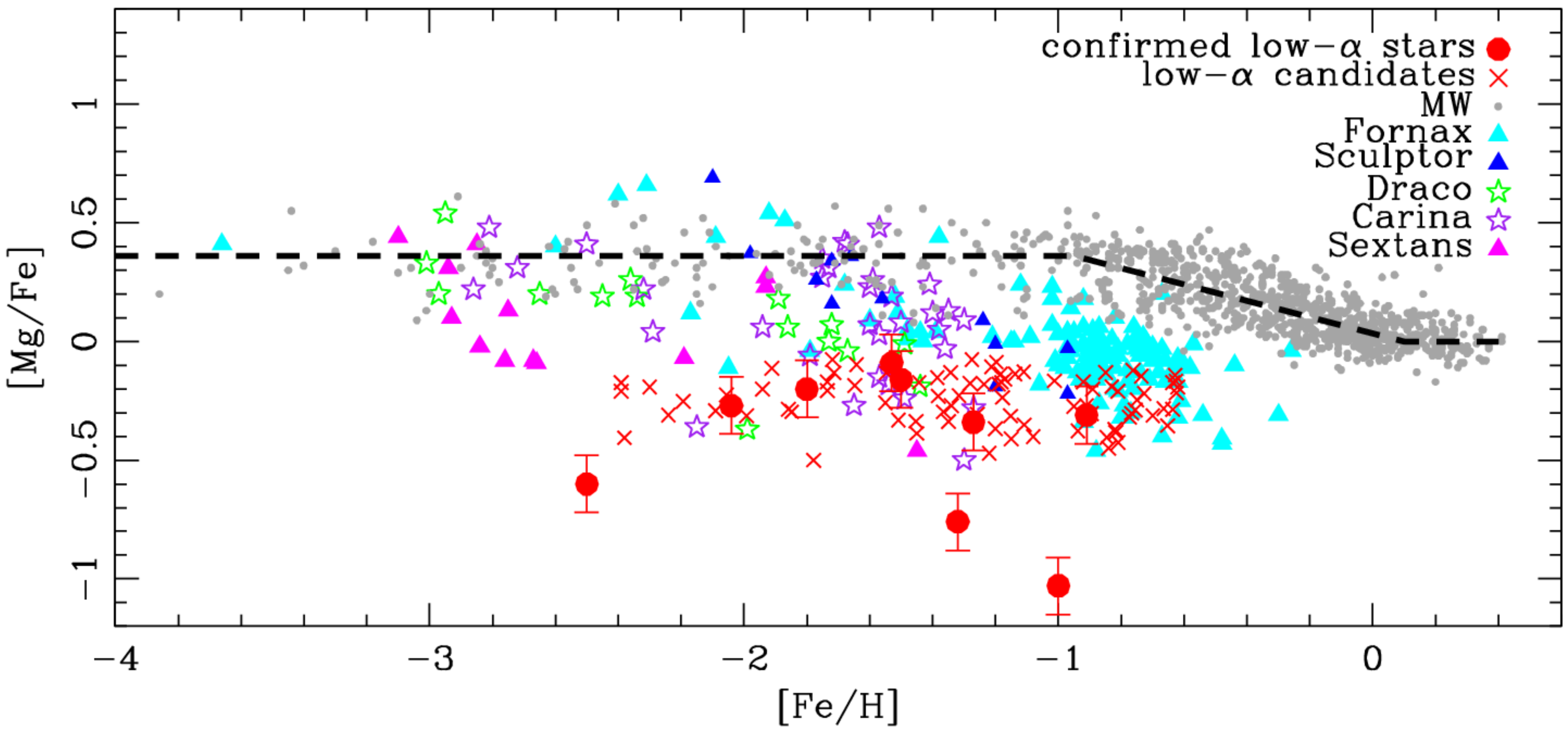






LAMOST-Subaru collaboration

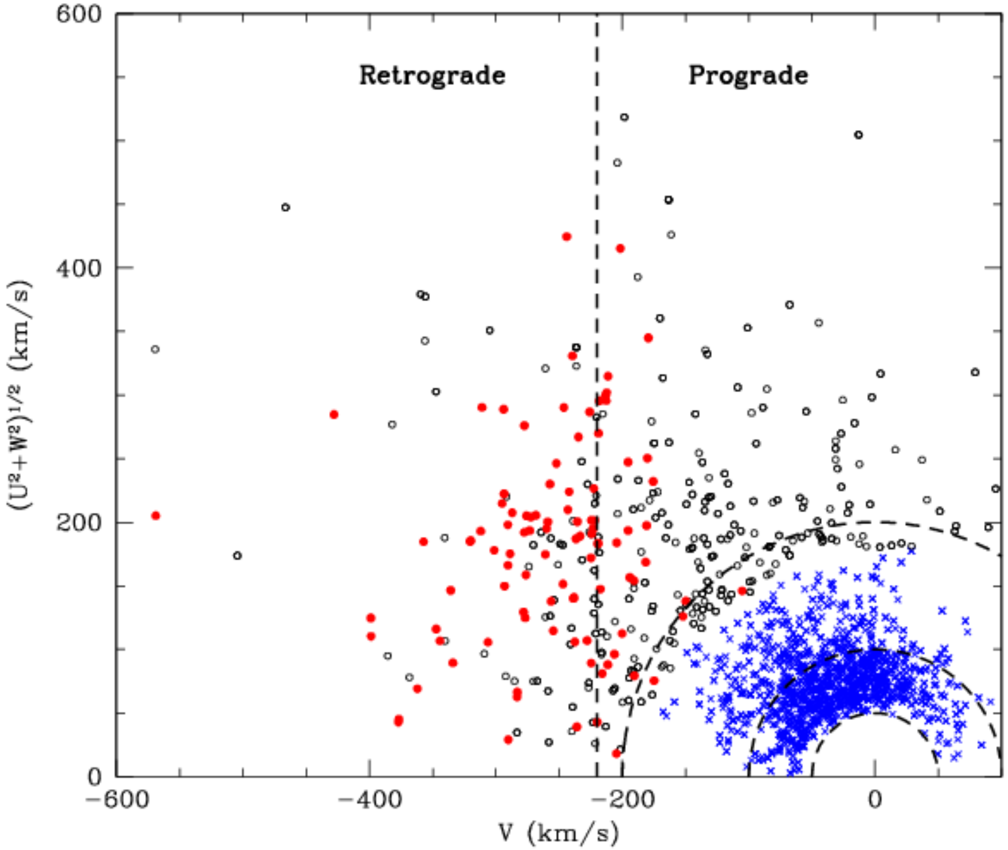
- **Candidate α-poor stars from LAMOST**
  - **more than 100 candidates**
  - **9 of them have been confirmed by Subaru/HDS**

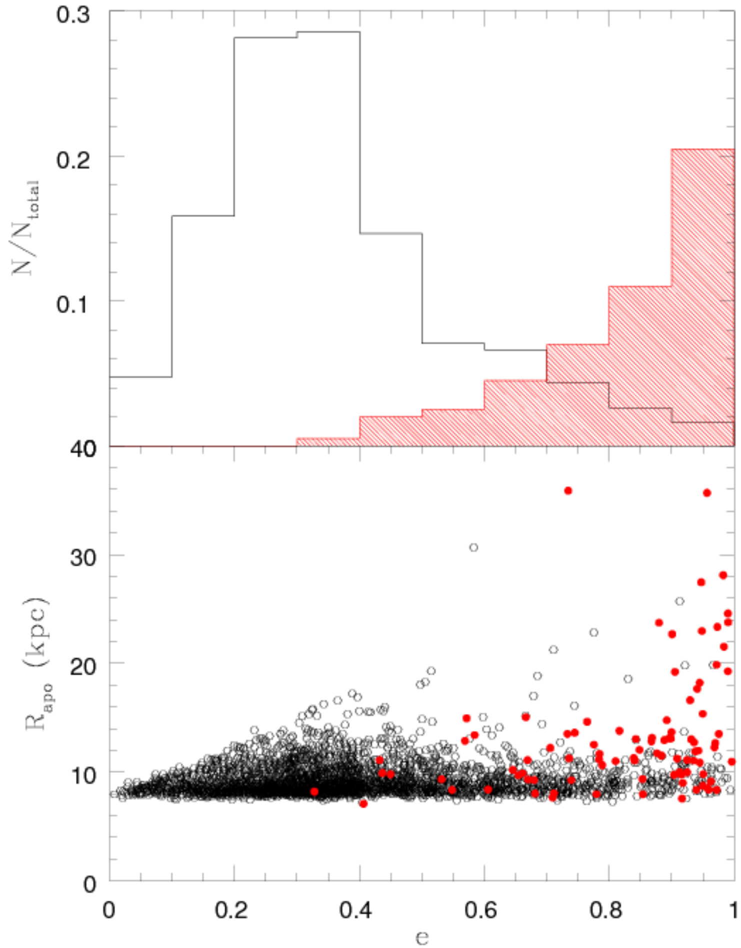


Orbits and kinematics of alpha-poor stars

- **Retrograde orbits**

large e and r_{apo}





LAMOST and Gaia data

Follow-up observation

Observation of high-resolution spectra:

➢ **LAMOST-Subaru collaboration**

- **Subaru/HDS observations:**

A star named LAMOST J1124+4535

February 2017

resolution ~45,000, 4000-6800 Å

SNR ~ 60 and 30 at 5,200 Å and 4,130 Å

- **Stellar parameters:**

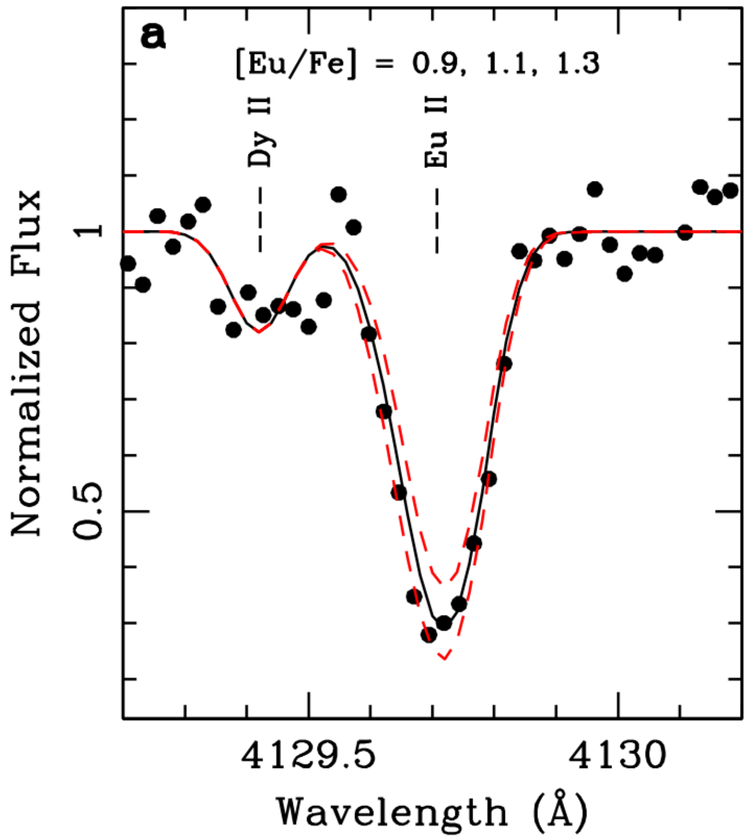
T_{eff}, logg, RV and microturbulent velocity from spectra

Abundance analysis

Chemical abundances for 24 elements (Xing et al. 2019)

Table 1 | Chemical abundances of J1124+4535

Element X	$\log(N_X/N_H+12)$	[X/Fe]	N_{lines}	σ
Fe I	6.23	0.00	95	0.10
Fe II	6.23	0.00	10	0.09
C (CH)	6.74	−0.42	-	0.20
Na I	4.08	−0.89	2	0.13
Mg I	6.02	−0.31	3	0.09
Si I	6.06	−0.18	4	0.08
Ca I	4.98	−0.09	12	0.08
Sc II	1.73	−0.15	6	0.09
Ti I	3.63	−0.05	8	0.09
Ti II	3.81	0.13	7	0.10
Cr I	4.04	−0.33	6	0.08
Mn I	3.84	−0.32	4	0.10
Ni I	4.60	−0.35	6	0.10
Zn I	2.92	−0.37	2	0.09
Sr II	1.24	−0.36	2	0.10
Y II	0.76	−0.18	4	0.13
Zr II	1.44	0.13	2	0.14
Ba II	1.15	0.24	4	0.12
La II	0.51	0.68	6	0.09
Ce II	0.72	0.41	4	0.13
Pr II	0.20	0.75	4	0.13
Nd II	0.81	0.66	15	0.14
Sm II	0.52	0.83	14	0.13
Eu II	0.35	1.10	1	0.10
Gd II	0.63	0.83	2	0.13
Dy II	0.74	0.91	2	0.15
Er II	<0.7	<1.05	1	-
Th II	<−0.16	<1.09	1	-

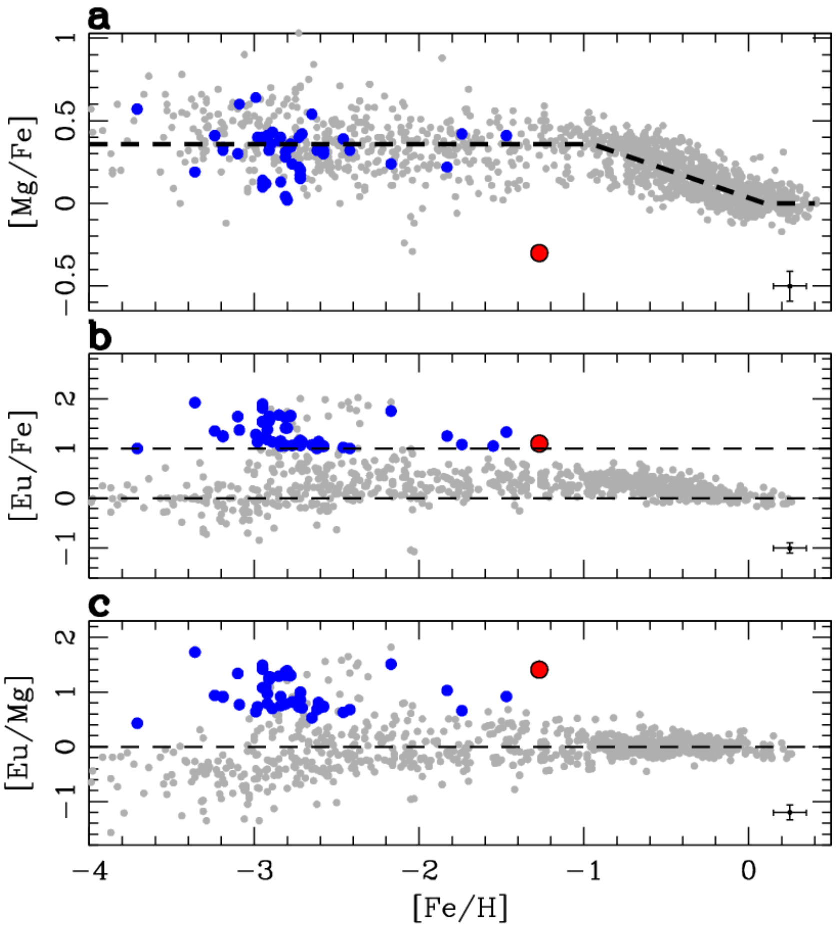


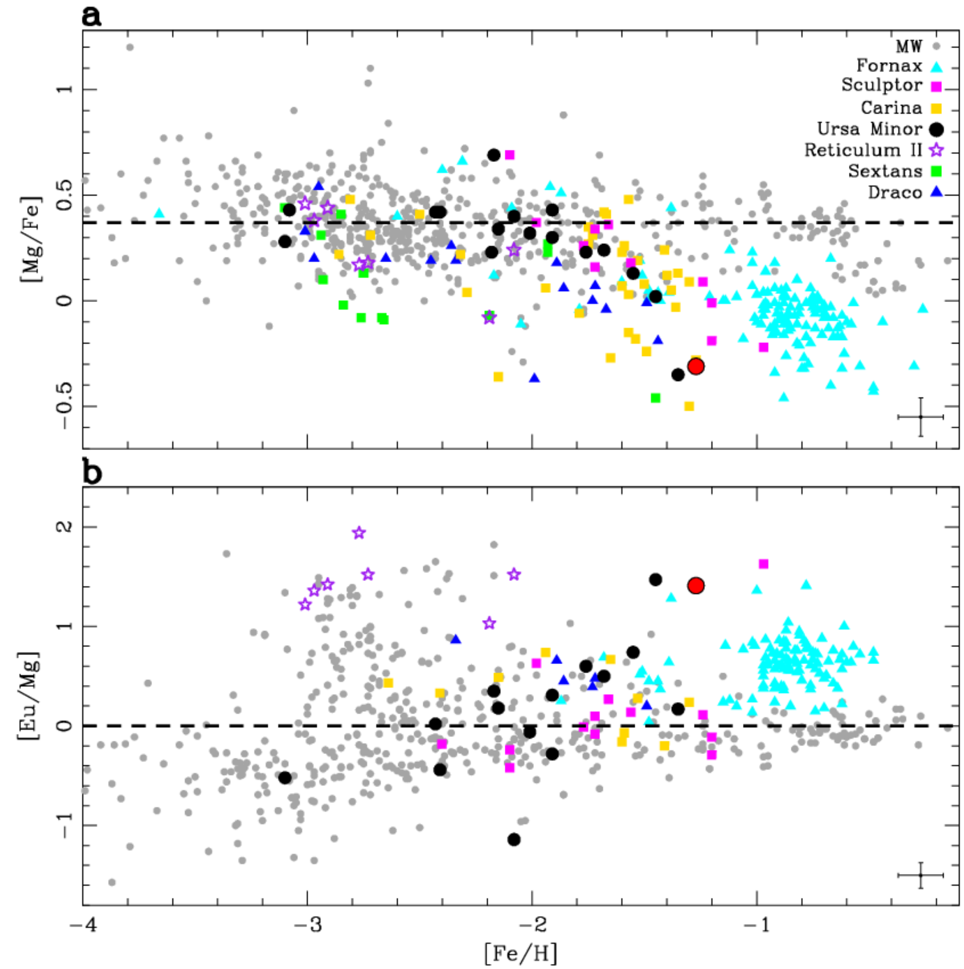
Determination of Eu abundance

[Eu/Fe] = 1.1 dex **r-II star!**

First alpha-poor r-II star in the halo: LAMOST J1124

[Mg/Fe] = -0.31, [Fe/H] = -1.27, [Eu/Fe] = 1.1





Signature of later accretion of satellite dwarf galaxy

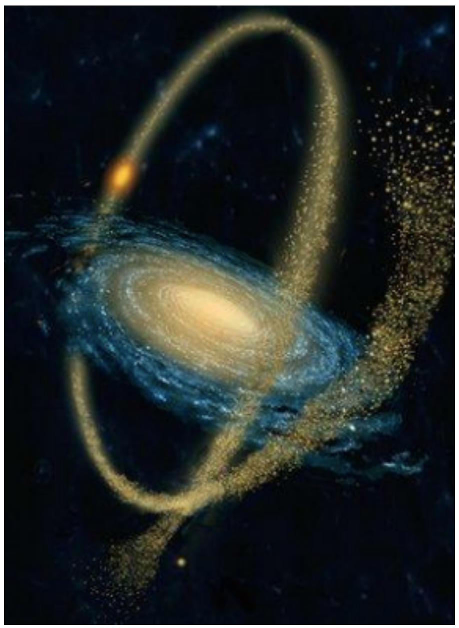
Comparison with stars in dwarf galaxies and the Galactic halo

Xing et al. NA, 2019

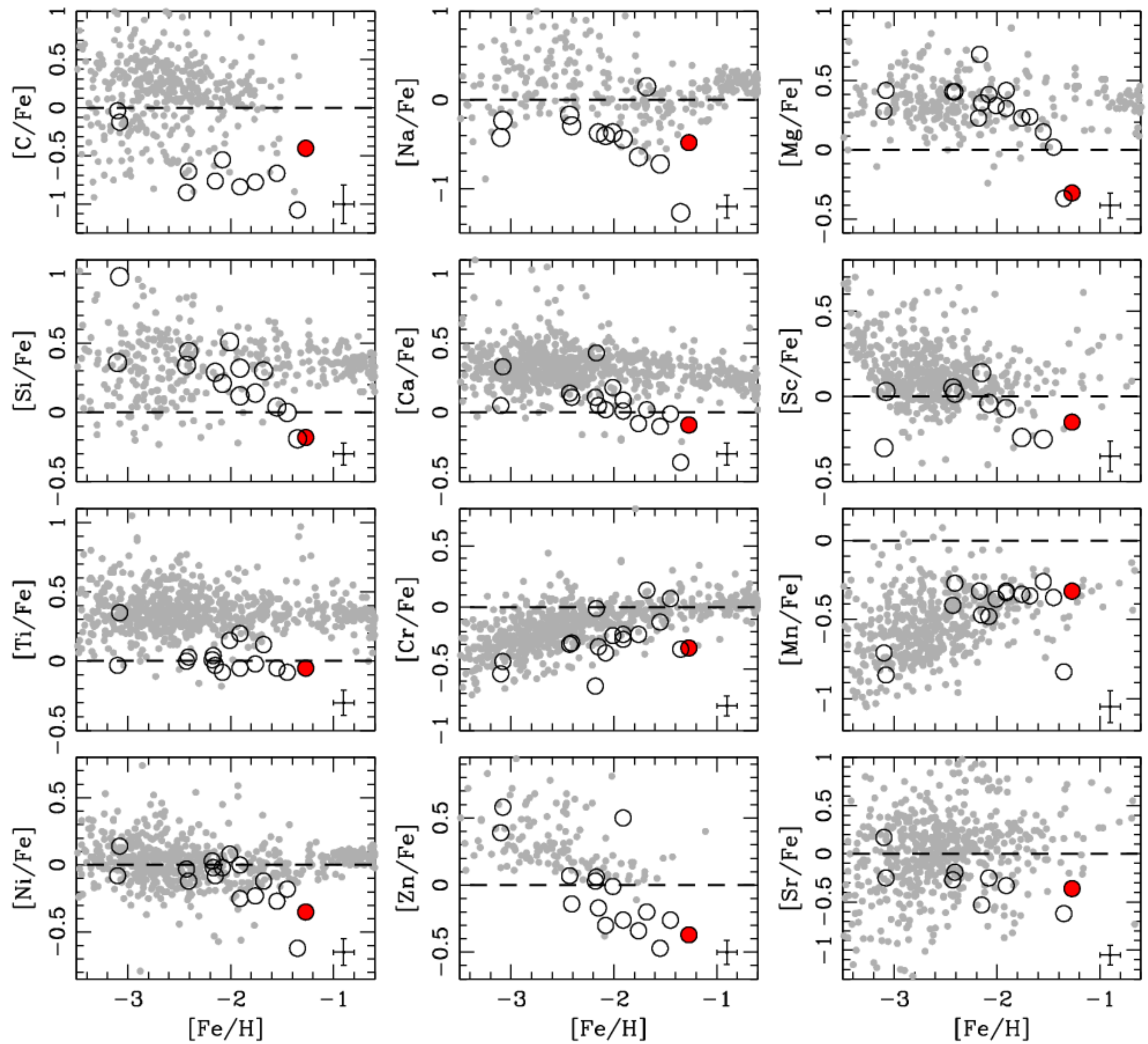
J1124 origin

Comparison with dwarf galaxy Ursa Minor stars and halo stars:

Xing et al. 2019



From a dwarf galaxy similar to UMi



First alpha-poor r-II star in the halo: LAMOST J1124

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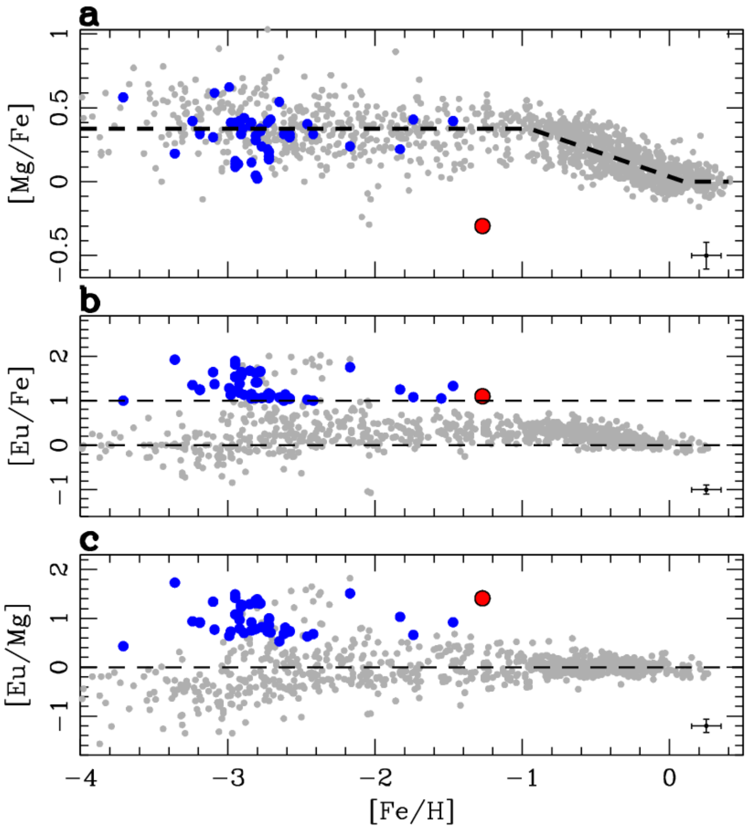
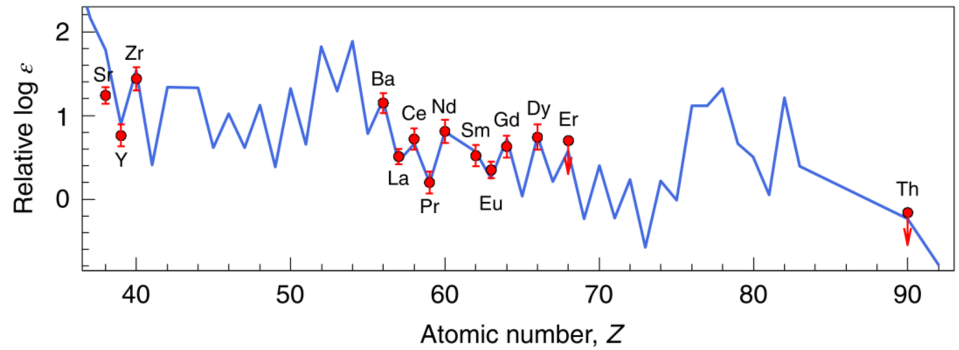


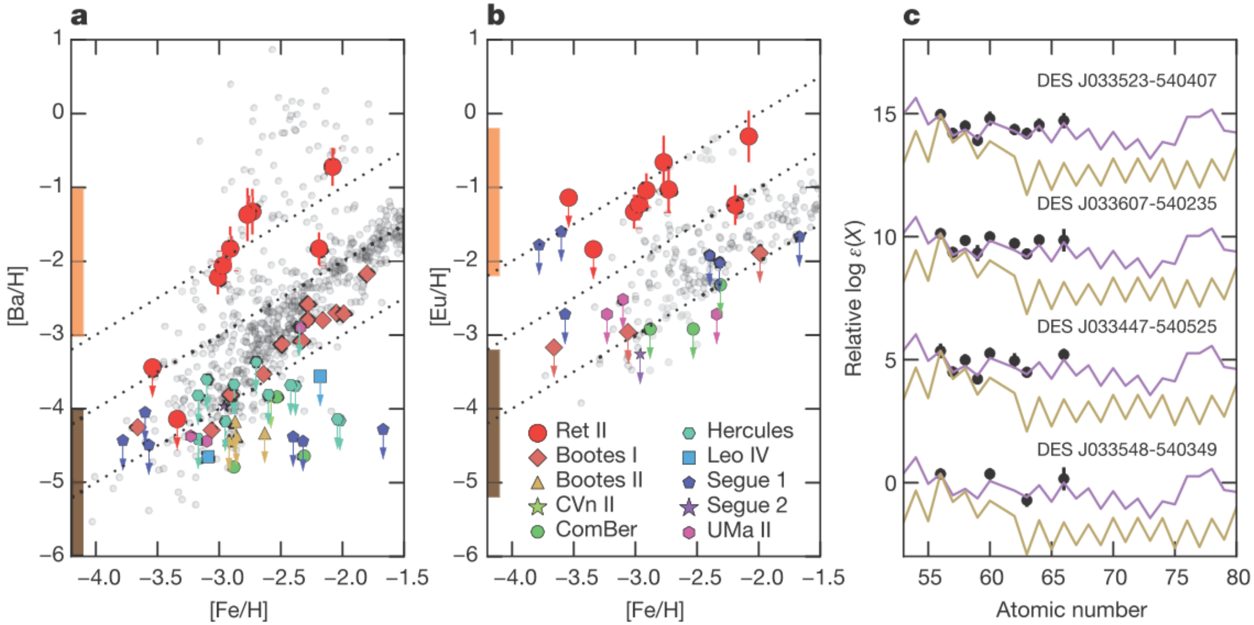


Comparison with the r-process component in solar system

the most metal-rich r-II Galactic star presently known!

- r- and s-process elements: heavier than zinc
- r-enhanced stars: ~5% of metal-poor stars in MW halo
- r-I: 0.3≤[Eu/Fe]≤1; r-II: 1<[Eu/Fe] (Beers & Christlieb 2005)
- abundance pattern for the heavy neutron-capture elements:
- follows the solar system r-process pattern

Reticulum II



Seven of the nine brightest stars in Ret II are r-II stars

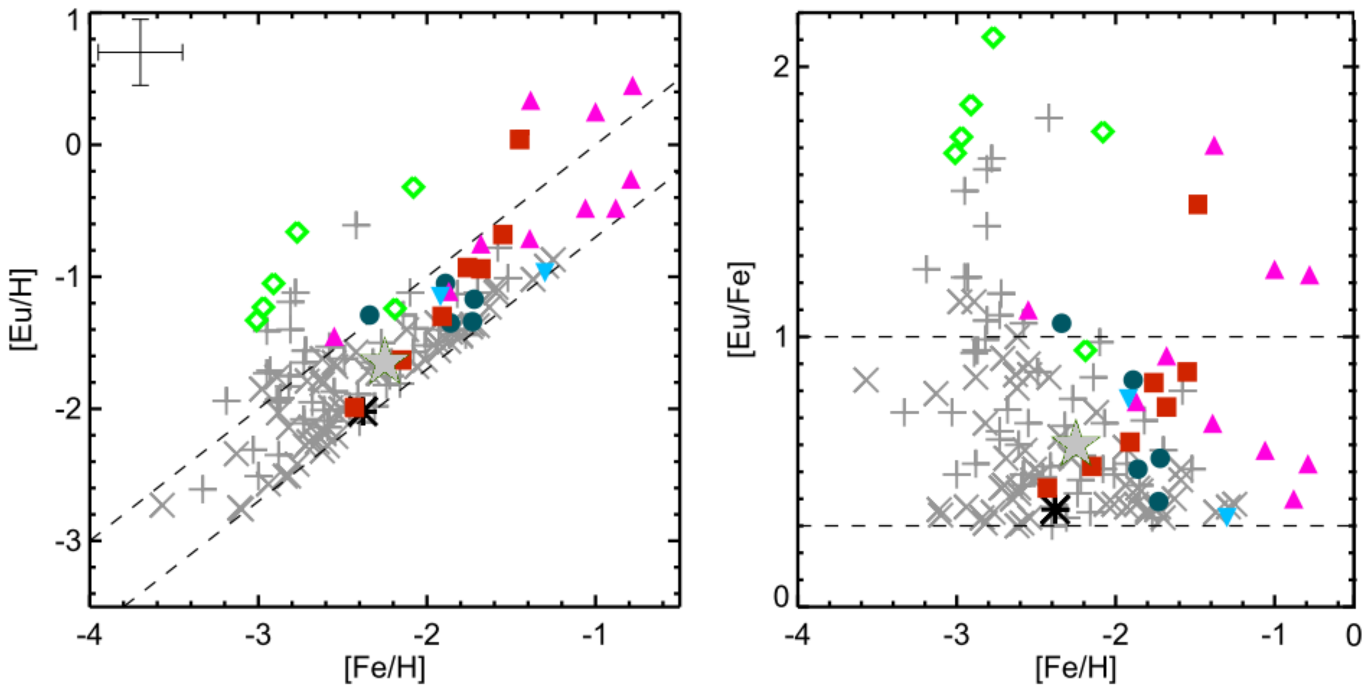
Ji et al. 2016

- No r enrichment in other nine UFDs:

. If each UFD were equally likely to host an r-process event, then the probability that N r-process events occurred in Ret II, but zero r-process events occurred in the other nine UFDs, is (1/10) ^N . There is thus only about a 1% chance that two or more events contributed to the r-process material in Ret II.

The neutron-capture material in Ret II was produced by just one event - neutron star merger

J1124 origin



Hansen et al. 2017

- Neutron star mergers: time delay
- r-II halo stars: -3<[Fe/H]<-1.27
- Environments with low star formation efficiencies: NSM occurred at relatively low metallicities

➢ High [Eu/Fe]

J1124 origin

Ji et al. 2016

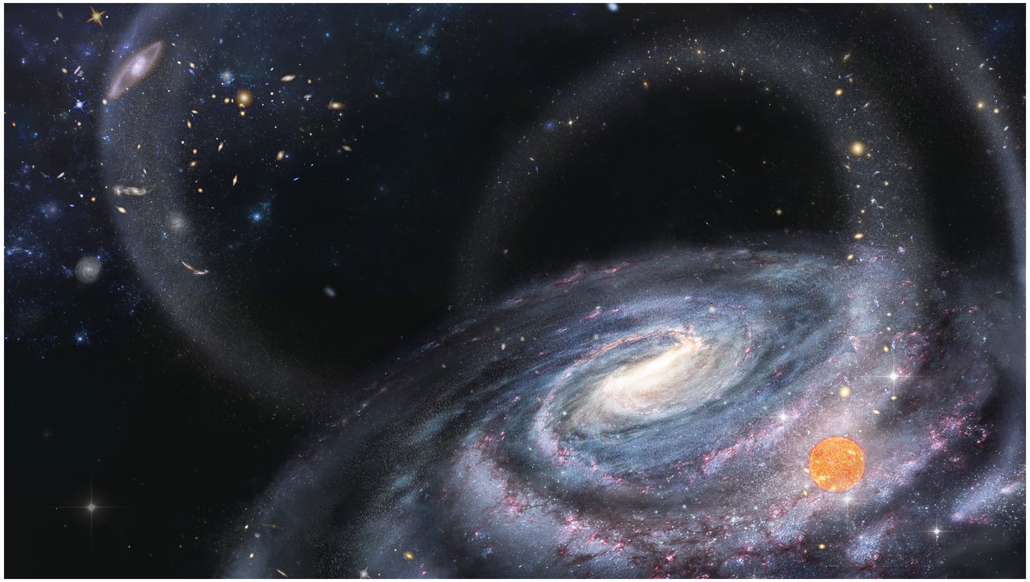
	Measure [Eu/H]	Mass of gas clouds	NSM simulations	GW170817 (Côté et al. 2018)
Dwarf galaxy Ret II	-1.3	10^5-10^7 $M_\odot$	$\sim 10^{-4.3\pm1}$ $M_\odot$ Eu	$\sim 10^{-4.7\pm0.5}$ $M_\odot$ Eu

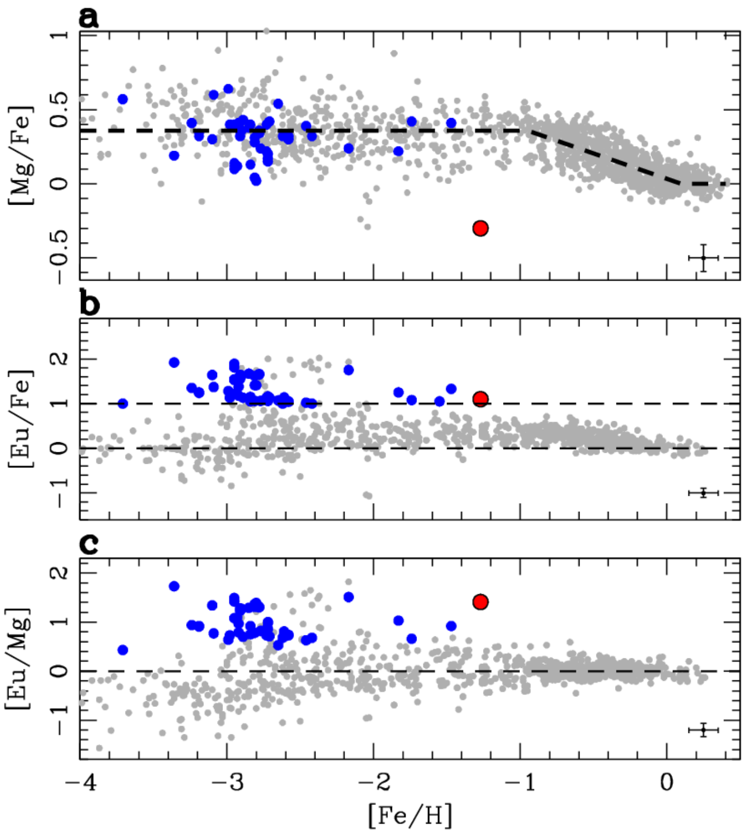
- Eu in the progenitor of J1124 ([Eu/H] = -0.17): pollution of a 10^5 $M_\odot$ cloud (**or smaller**) by a rare r-process event
- A challenge to model efficient capture of the energetic ejecta in such low-mass gas cloud

Summary

- J1124 : the strong evidence for accretion of a dwarf galaxy
- Halo stars with alpha deficiency and extreme r-process enhancement

can be tagged to dwarf galaxies disrupted by the MW





Thank you!