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NLTE spectroscopy of metal-poor stars

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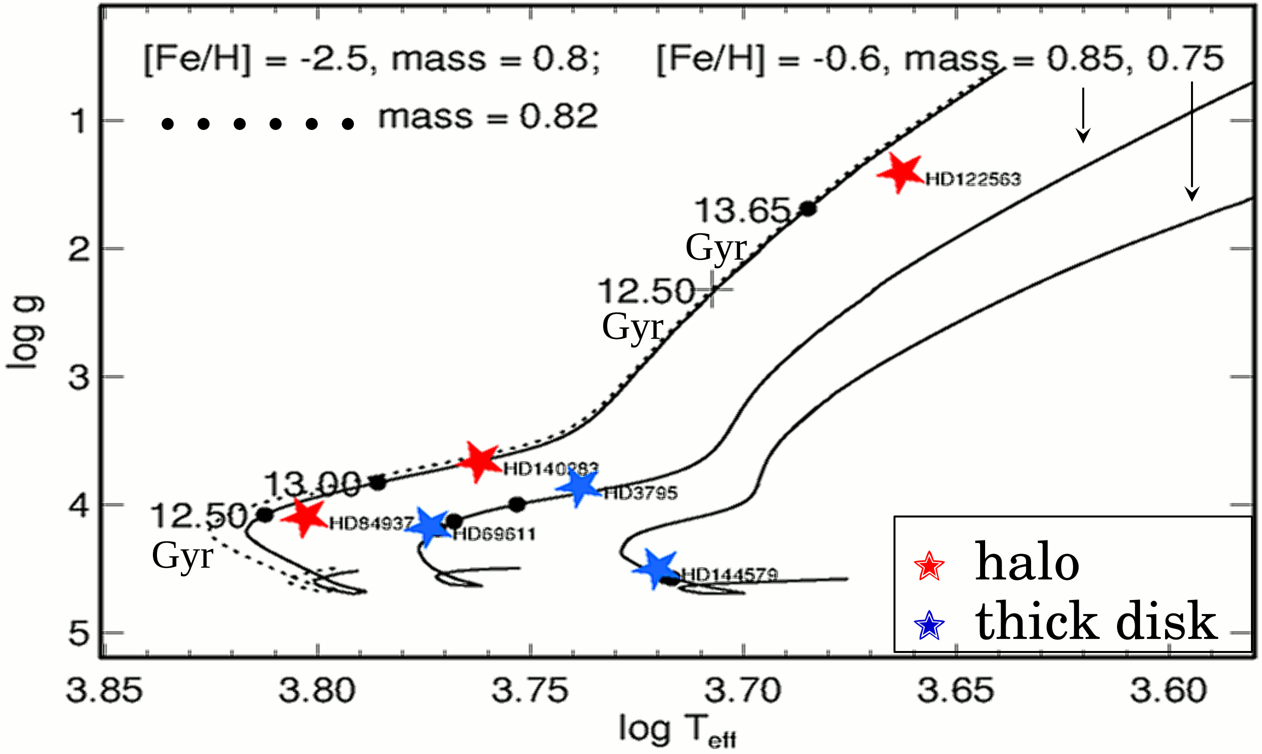
Elemental abundances versus star ages (τ) would be perfect, but, in most cases, accuracy of star's age is poor.

- Most Galaxy field stars: τ from evolutionary tracks.
- Metal-poor stars: uncertainty in τ is ~1 Gyr.



- HD122563 ([Fe/H] = -2.5), halo benchmark star does not sit on its evolutionary track

Evolutionary tracks (*Yi*+ 2001)

Aims

Homogeneous, multi-element abundance analysis

in -4 < [Fe/H < 0.2 range.

Collaborators

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Outline of this talk

- Stellar sample, observations
- Modelling of spectral line formation: why NLTE ?
- Atmospheric parameters
- Galactic abundance trends
- Observations versus Galactic chemical evolution models

- Stellar sample

71 nearby
(d < 0.5 kpc)
dwarfs, subgiants
$-2.6 \leq [Fe/H] \leq 0.2$

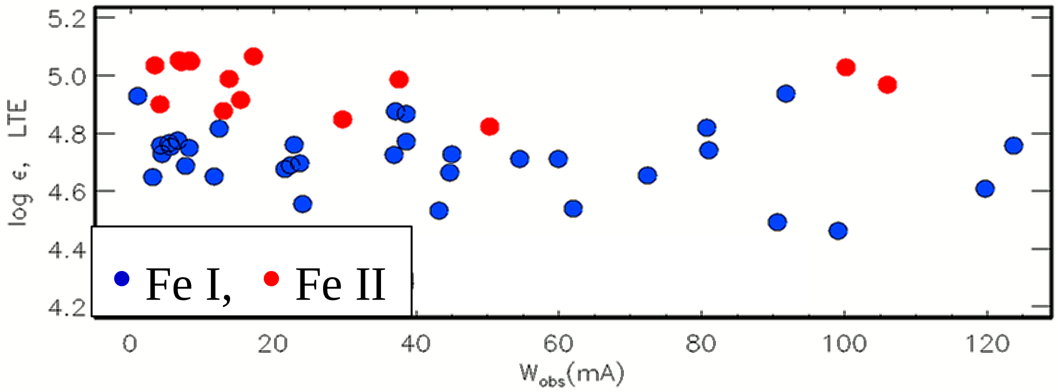
23 halo giants
(d < 8 kpc)
$-4 < [Fe/H] < -1.7$
no C-enhanced

$[Fe/H] = \log(N_{Fe}/N_{H})_{star} - \log(N_{Fe}/N_{H})_{sun}$

- Observations: R > 40 000, S/N > 100

Hamilton/Shane (Lick obs., USA)
FOCES/2.2m (Calar Alto obs., *K. Fuhrmann*)
UVES/VLT2, ESPaDOnS/CFHT archives
MIKE/Magellan (Las Campanas obs., *R. Ezzeddine*)
HIRES/Keck I (published EWs, *Cohen*+ 2013, ApJ, 7788, 56)

◆ Method of calculations: without assuming LTE (NLTE approach). Why?



HD 122563, reliable parameters:

$T_{\rm eff}$ = 4640±40 K (*Karovicova*+ 2018)

log g =1.4±0.06 (Gaia DR2)

LTE: Fe I - Fe II = -0.25 dex

Minority species (Fe I, Al I, Ca I, ...):

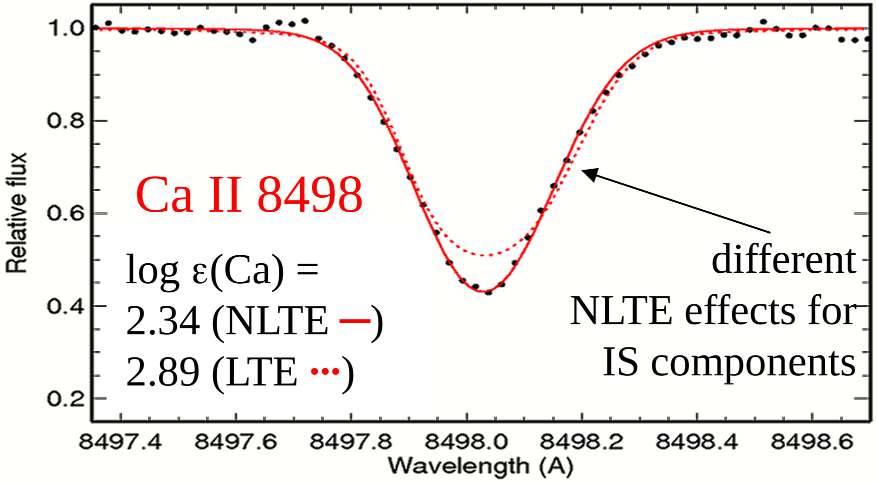
- number density is sensitive to $J_{\rm thr} / B_\nu$
- $J_{\rm UV} / B_\nu > 1$ ⇨ overionisation, $N_{\rm NLTE} < N_{\rm LTE}$

departures from LTE are highly likely

✓ LTE underestimates spectroscopic log g:

Cool VMP giants, Fe I - Fe II = -0.25 dex ⇨ Δ log g ~ -0.3

✓ LTE profiles do not fit to the cores of strong lines



HE 0557-4840

$T_{\rm eff}$ = 5100 K, log g = 2.2, [Fe/H] = -4.8

Ca II IR triplet lines:

- LTE profiles are too shallow,

- perfect NLTE fits (*Sitnova*+ 2019)

Majority species (Ca II, Fe II, Ti II): $N_{\rm NLTE} = N_{\rm LTE}$.

Departures from LTE for populations of excited levels:
- photon loss in spectral lines,
- radiative pumping the UV transitions.

Stellar atmospheres: what is meant by NLTE?

- ✓ Do not use Saha-Boltzmann equations,
- ✓ atomic level populations n_i from statistical equilibrium (SE) equations,

$$\sum_{j\neq i} n_j \left(R_{ji}+C_{ji}\right)=n_i \sum_{j\neq i}\left(R_{ij}+C_{ij}\right) \quad i=1,\ldots NL$$

Real atomic term structure is represented by the model atom with *NL* levels

+

$$\mu\frac{dI_\nu(z,\mu)}{dz} = -\chi_\nu(z)I_\nu(z,\mu)+\eta_\nu(z)$$

$R_{ij}(J_\nu)$ - radiative rates,

$C_{ij}(T,N)$ - collisional rates

- ✓ solution of coupled SE and radiative transfer equations
- ✓ Maxwellian velocity distribution, with $T_e = T_A = T_i$,

Take care !

- Completeness of model atom
- Accuracy of atomic data

Used NLTE methods

	Li I	*Shi*+ 2007
	C I	*Alexeeva*, *ML*, 2015
✓	O I	*Sitnova*, *ML*, 2013, 2018
✓	Na I	*Alexeeva*+ 2014
✓	Mg I	*ML*, 2013
✓	Al I	*Baumüller & Gehren*, 1996
✓	Si I-II	*Shi*+ 2008
	K I	*Zhang*+ 2006
✓	Ca I-II	*ML*+ 2007, 2017
	Sc II	Zhang+ 2008
✓	Ti I-II	*Sitnova*+ 2016
✓	Fe I-II	*ML*+ 2011
	Cu I	*Shi*+ 2014
✓	Sr II	*Belyakova*, *ML*, 1997
	Zr I-II	*Velichko*+ 2010
✓	Ba II	*ML*+ 1999
✓	Eu II	*ML*, *Gehren*, 2000

NLTE abundance corrections, electronic tables:
http://www.inasan.rssi.ru/~lima/NLTE_corrections/

Online: http://spectrum.inasan.ru/nLTE/

◆ Homogeneous set of atmospheric parameters

Photometric T_{eff}

Dwarf sample: IRFM (*Casagrande*+ 2010, 2011; *Alonso*+ 1996; *Gonzalez Hernandez & Bonifacio* 2009)

Giant sample: *V-I-J-H-K* colours, calibration of *Ramírez & Meléndez* (2005)

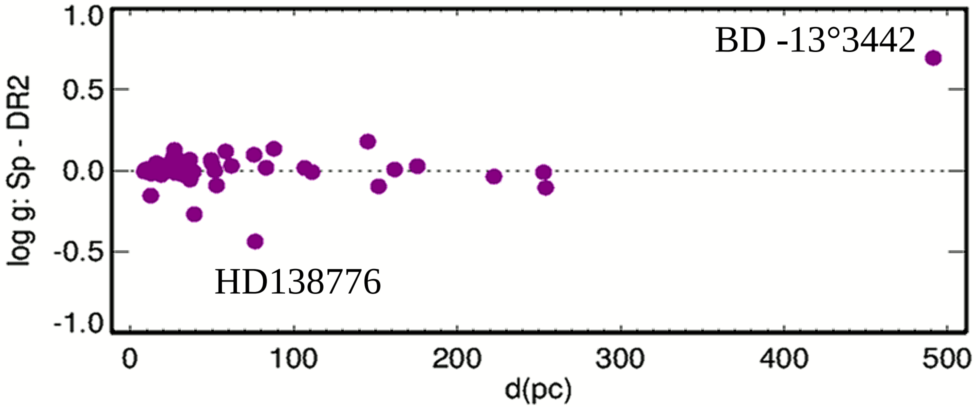
Spectroscopic $\log g_{\mathrm{sp}}$, [Fe/H], V_t } NLTE analysis of Fe I/Fe II

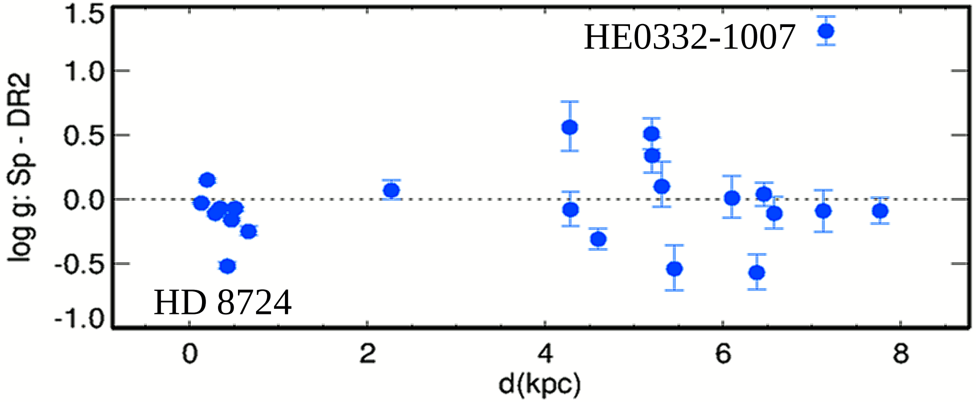
- NLTE code: DETAIL (*Butler, Giddings* 1985, updated), the NLTE element is treated as a trace one.
- Model atmospheres: 1D MARCS (*Gustafsson*+ 2008).

Sitnova+ 2015; *ML*+ 2017; *ML*+ 2019

Verification of spectroscopic method

Differences between spectroscopic and Gaia based log g





Dwarf sample

Δlog g(Sp - Gaia) = 0.01±0.14

Giant sample,

Sp ≈ Gaia for d $\lesssim$ 2 kpc,

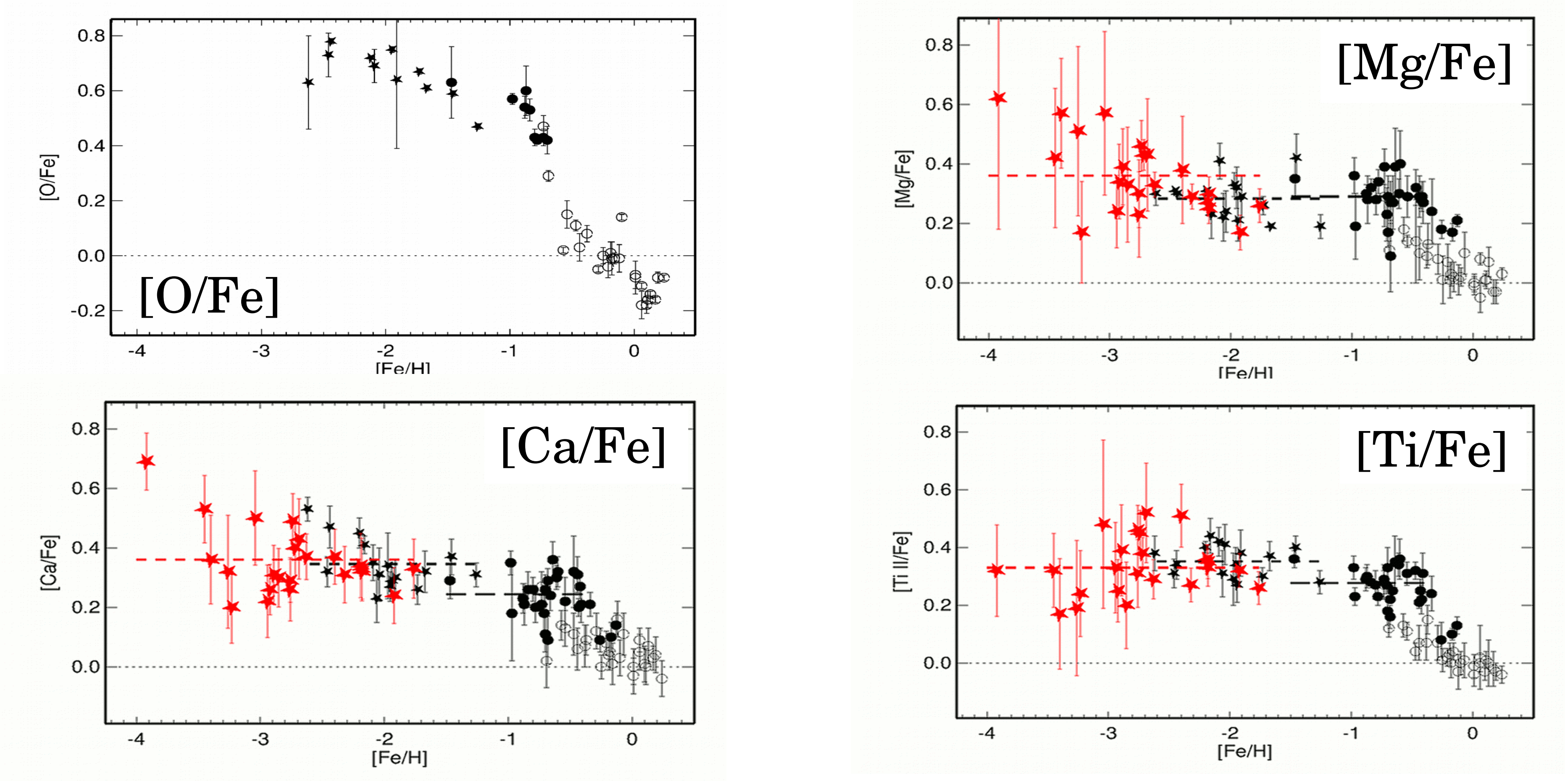
scatter for d > 4 kpc.

Fe I/Fe II in 1D-NLTE is well working.

Spectroscopy remains the main tool for distant stars.

Gaia distances from *Bailer-Jones*+ (2018, AJ, 156, 58)

[α/Fe] - [Fe/H] trends in Milky Way

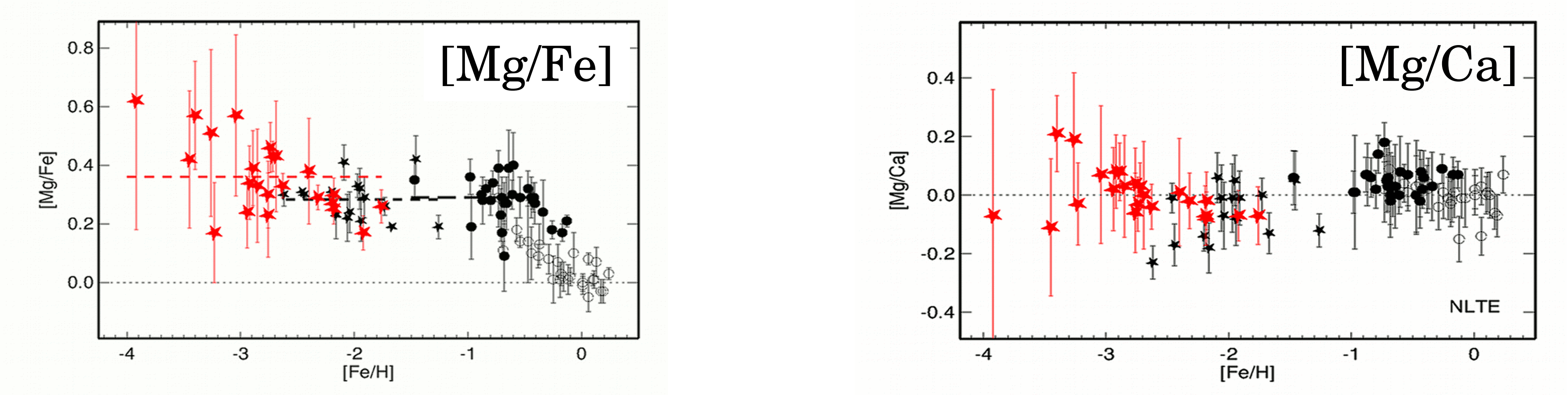


○ thin disk ● thick disk

★ halo dwarfs ★ halo giants

Zhao+ 2016; *ML*+ 2017;
Sitnova, *ML* 2018; *ML*+ 2019

[α/Fe] - [Fe/H] trends, halo (★ dwarfs ★ giants)



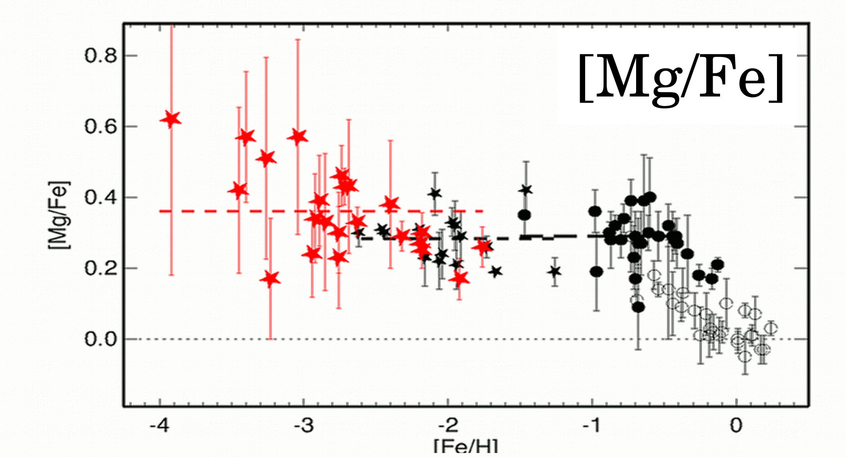
- [α/Fe] ~ 0.3 for each of Mg, Ca, Ti,
- for both nearby and distant objects ⇒ universality of chemical evolution
- [O/Fe] > [Mg, Ca, Ti/Fe], grows at [Fe/H] < -0.9,
- [Fe/H] < -2.6: scatter in [α/Fe] increases, ⇒ incomplete mixing

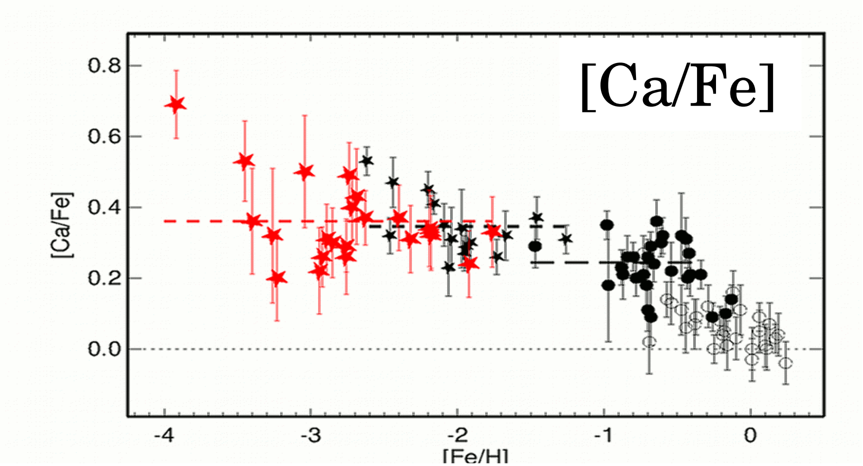
  but does not in ratios among α-elements.

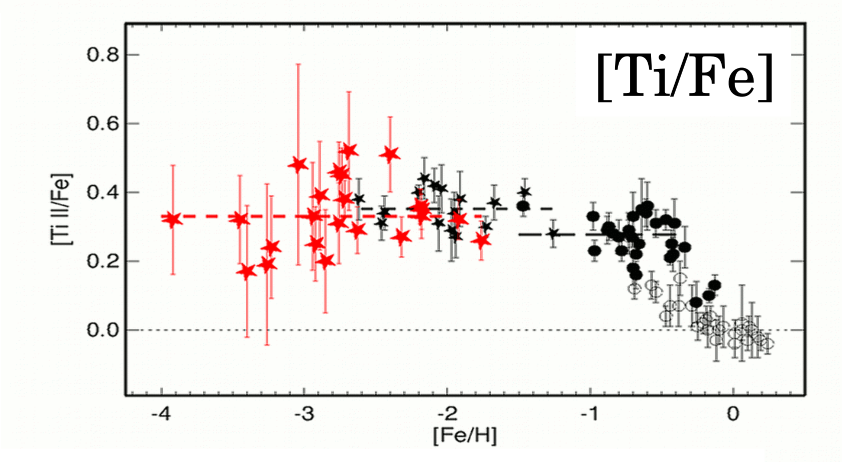
[α/Fe] - [Fe/H] trends, thick disk (•)

- Thick disk, [Fe/H] < -0.4

[α/Fe] ≈ 0.3 for each Mg, Si, Ca, Ti
In line with
Ishigaki+ (2012),
Bergemann+ (2017, Mg)

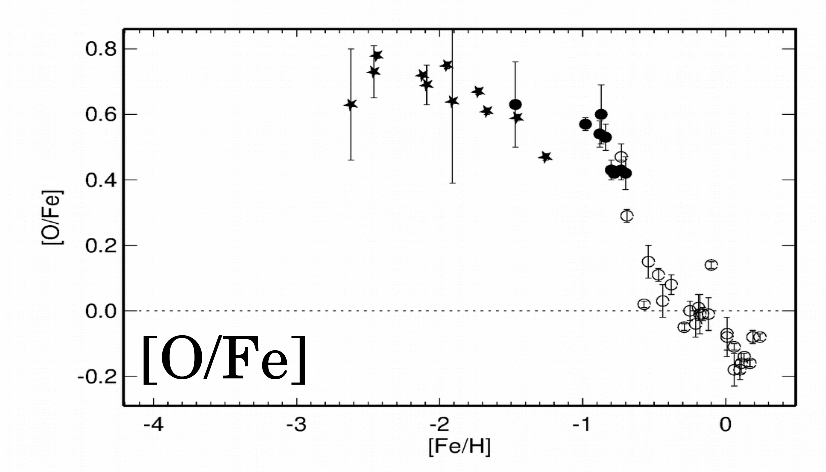


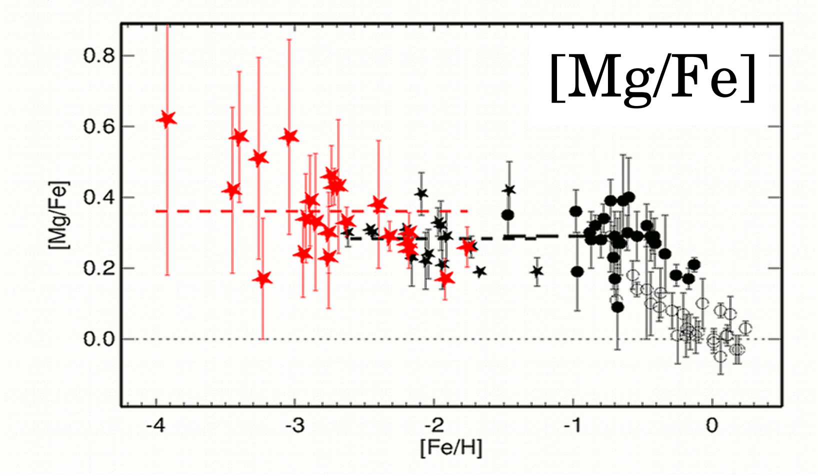




- Thick disk, [Fe/H] > -0.4: decline of [α/Fe] ⇒ SNeIa

[α/Fe] - [Fe/H] trends, thin disk





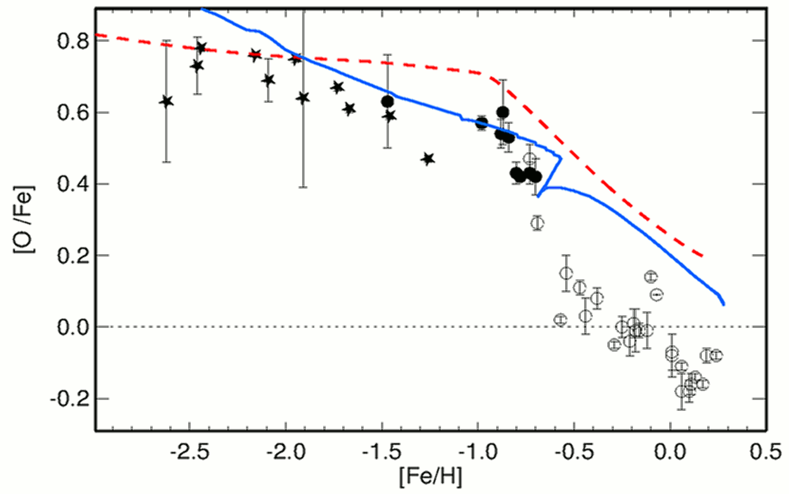
Thin disk (○), -0.7 ≤ [Fe/H] ≤ 0.25

- [α/Fe] grows towards lower [Fe/H],
- lower than for thick disk at given [Fe/H].

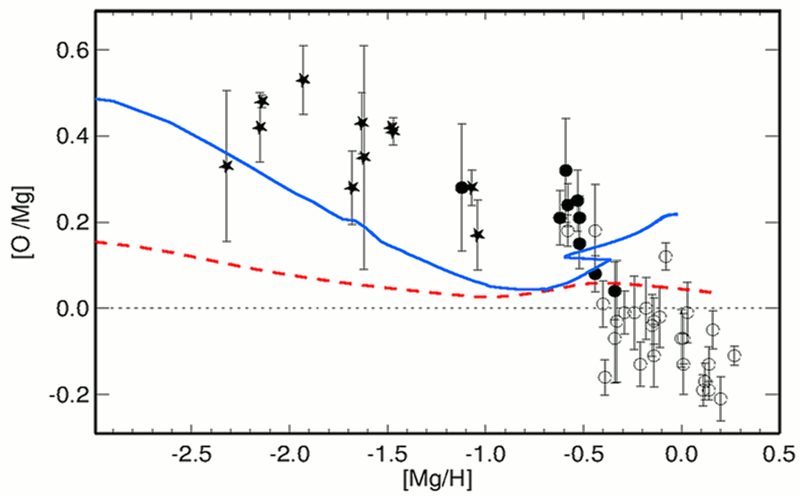
In line with
Fuhrmann (1998, Mg), *Adibekyan*+ (2012), *Bensby*+ (2014), ...

Observations versus GCE models: [O/Fe] and [O/Mg]

GCE models
——— R10 (*Romano*+ 2010, A&A, 522, A32)
- - - K15 (*Kobayashi*2015, as given in *Sneden*+ 2016, ApJ, 817, 53)



○ thin disk
● thick disk
✫ halo

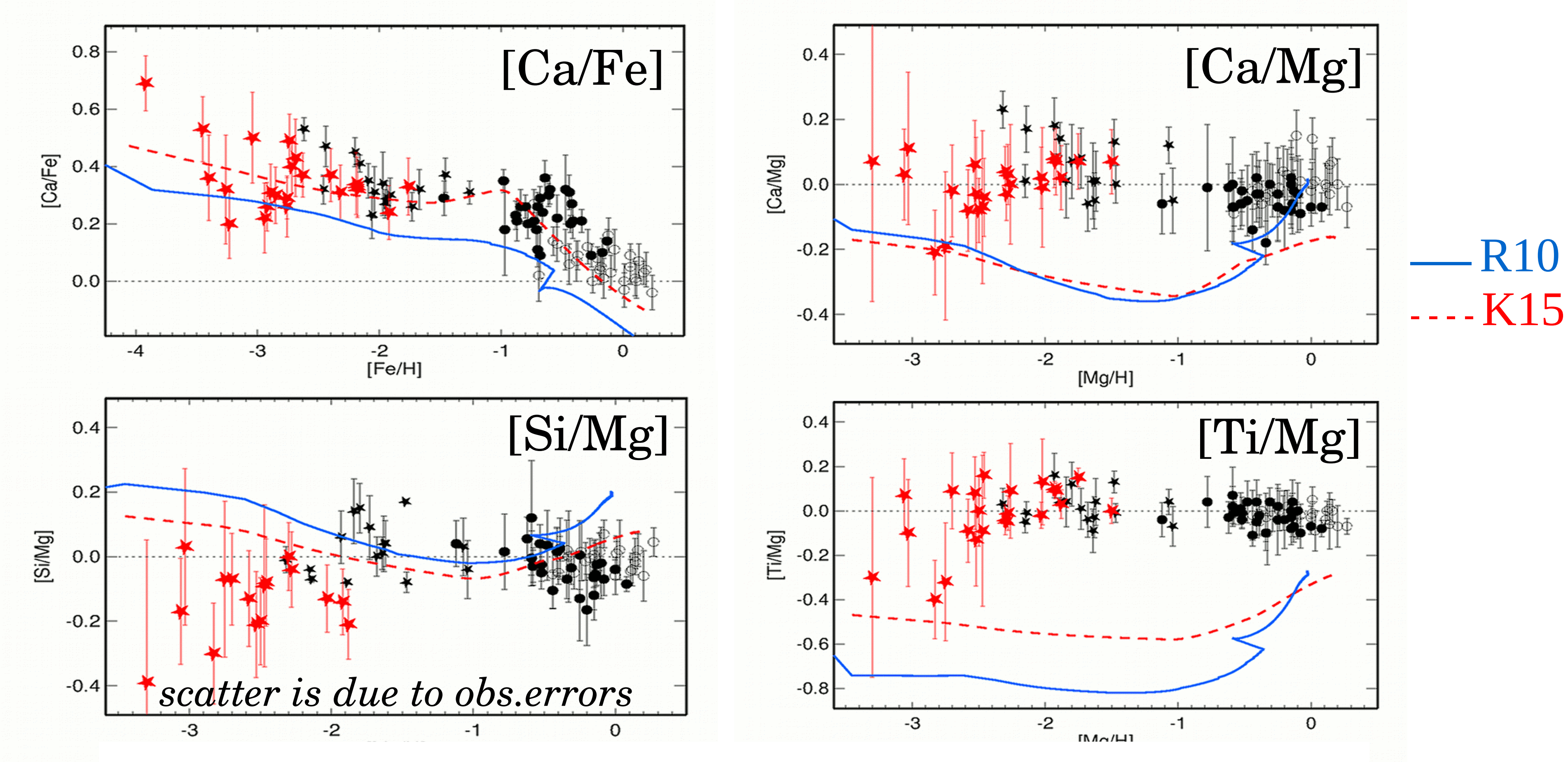


K15 is fine:

- ✓ [Fe/H]$_{\text{knee}}$ ~ -0.9,
- ✓ slopes for [Fe/H] > -0.9
- ✓ and < -0.9.

Models do not reproduce observed [O/Mg] $\gtrsim$ 0.3 for [Mg/H] < -1.

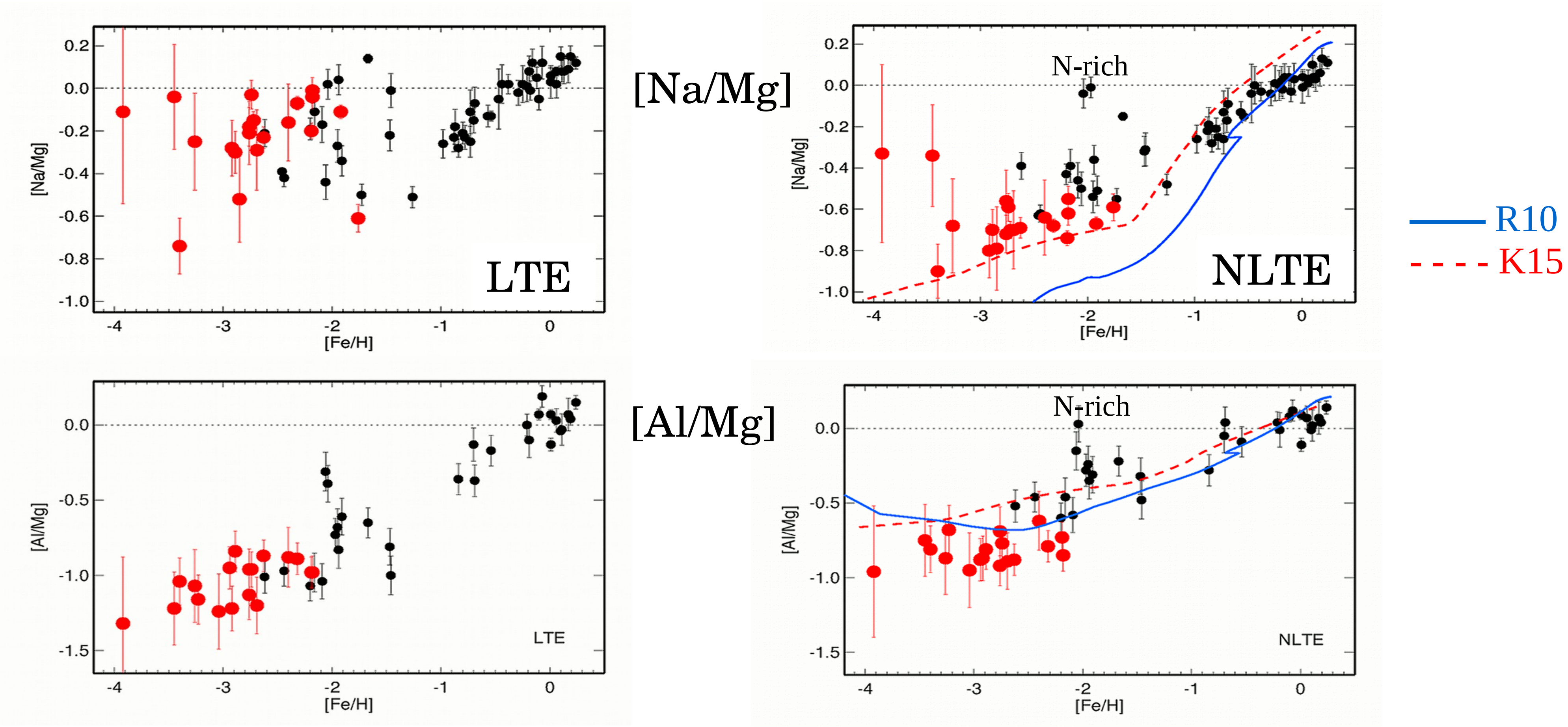
Observations versus GCE models: α-elements



scatter is due to obs.errors

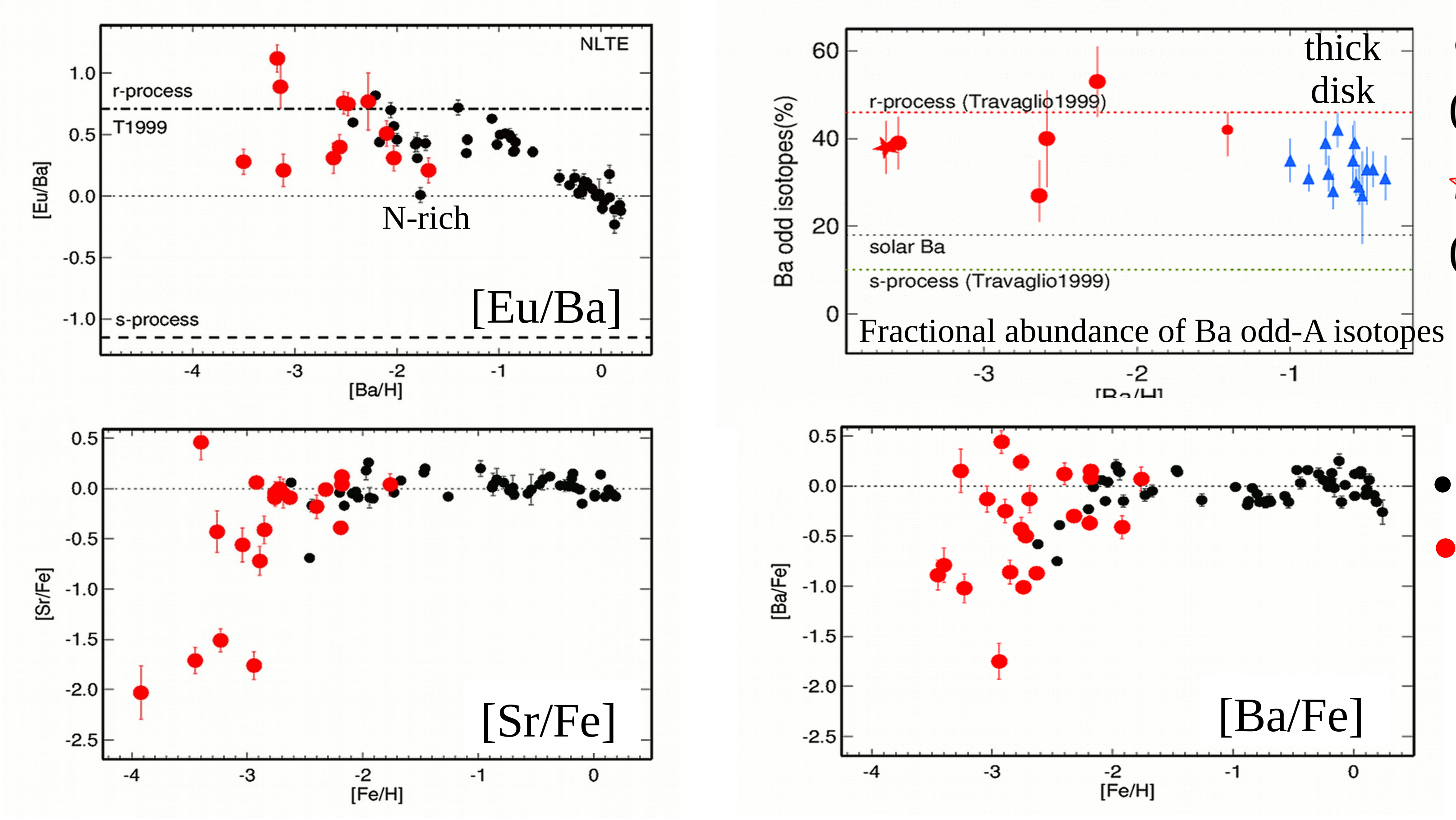
GCE models:
produce too much Mg, Si, but underproduce Ti.

Observations versus GCE models: Na/Mg and Al/Mg



Observational data take advantage of NLTE !

Eu/Ba, Sr/Fe, Ba/Fe — typical for Galaxy field stars



● halo
(*ML*, *Belyaev* 2019)

☆ HD 140283
(*Gallagher*+ 2015)

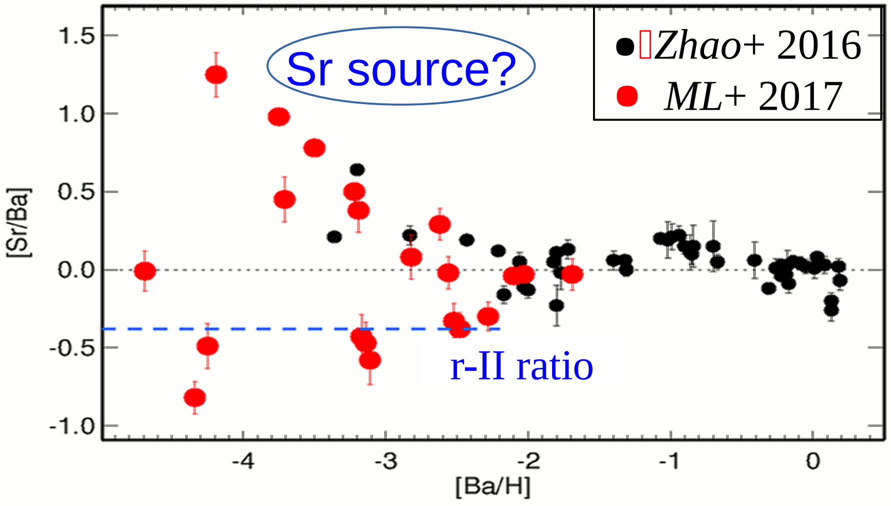
● dwarfs (*Zhao*+ 2016)

● giants (*ML*+ 2017)

✓ Halo stars: [Eu/Ba] > 0.2, $f_{\rm odd} \simeq f_{\rm odd,r} = 0.46 \Rightarrow$ r-process is at work

✓ [Ba/H] > -1: contribution of the main s-process.

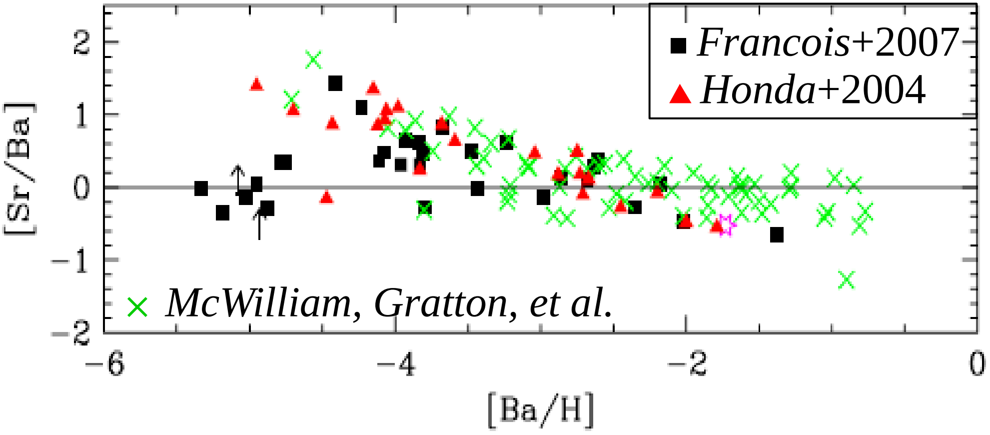
Sr/Ba trends in Milky Way



✓ [Ba/H] > -2, [Sr/Ba] ≃ 0
common origin of Sr, Ba, r-, s-process.

✓ [Ba/H] < -2, two branches:
(i) [Sr/Ba] ~ -0.5 ⇒ r-process?

Compare with r-II stars:
$[\mathrm{Sr/Ba}]_{\mathrm{r\text{-}II}} \simeq -0.4$



(ii) Sr/Ba rises towards lower Ba ⇒
2nd channel of Sr production.
Type of nuclear reactions?
Astrophysical site?

Summary

- The homogeneity of data is essential for searching for and discussing evolutionary changes in elemental abundances.

- Multi-element abundance analysis for 94 stars in $-4 \lesssim$ [Fe/H] $\lesssim 0.2$, constraints to the GCE models:
  - ✓ (Si, Ca, Ti)/Mg are solar for entire range of [Mg/H],
  - ✓ [O/Mg] $\gtrsim 0.3$ for [Mg/H] < -1,
  - ✓ halo and thick disk ([Fe/H] < -0.4): [α/Fe] $\simeq 0.3$,
  - ✓ thick disk ([Fe/H] > -0.4): decline of [α/Fe],
  - ✓ [Fe/H] $\lesssim -2.6$, α/Fe reveals incomplete mixing,
  - ✓ [Ba/H] < -2, two branches of Sr/Ba.