Stellar Abundances

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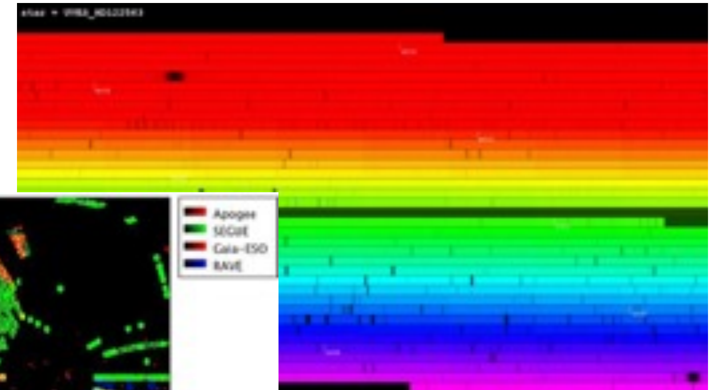
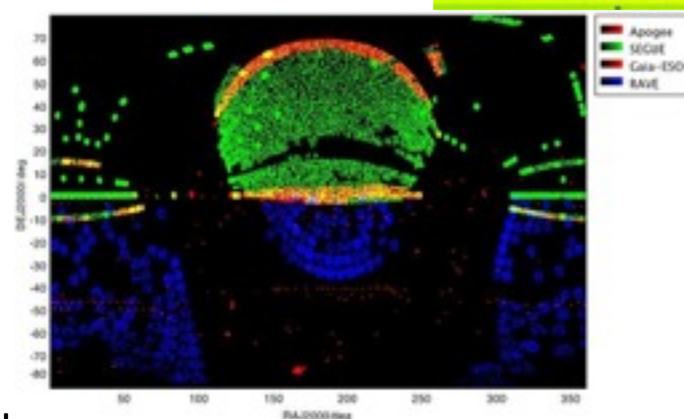
Outline

- Motivation
- Abundance measurements in cool stars
- Chemical evolution models:
  - successes
  - unknowns
- Conclusions

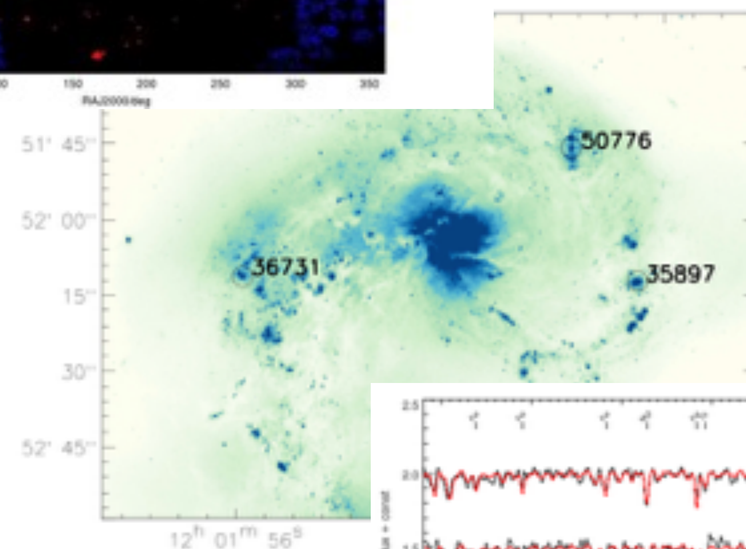
Motivation

Late type stars:
all stellar populations
-6 < [Fe/H] < +0.5
30 - 50 elements: **He, Li … , U**
several ionization stages
Sun as a reference

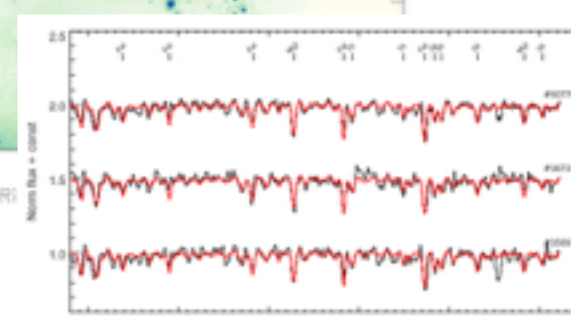




Huge observational datasets:
large stellar surveys
SEGUE, Gaia-ESO, APOGEE, Galan,
total ~ 2 million spectra
4MOST (*2021): + 20 million spectra

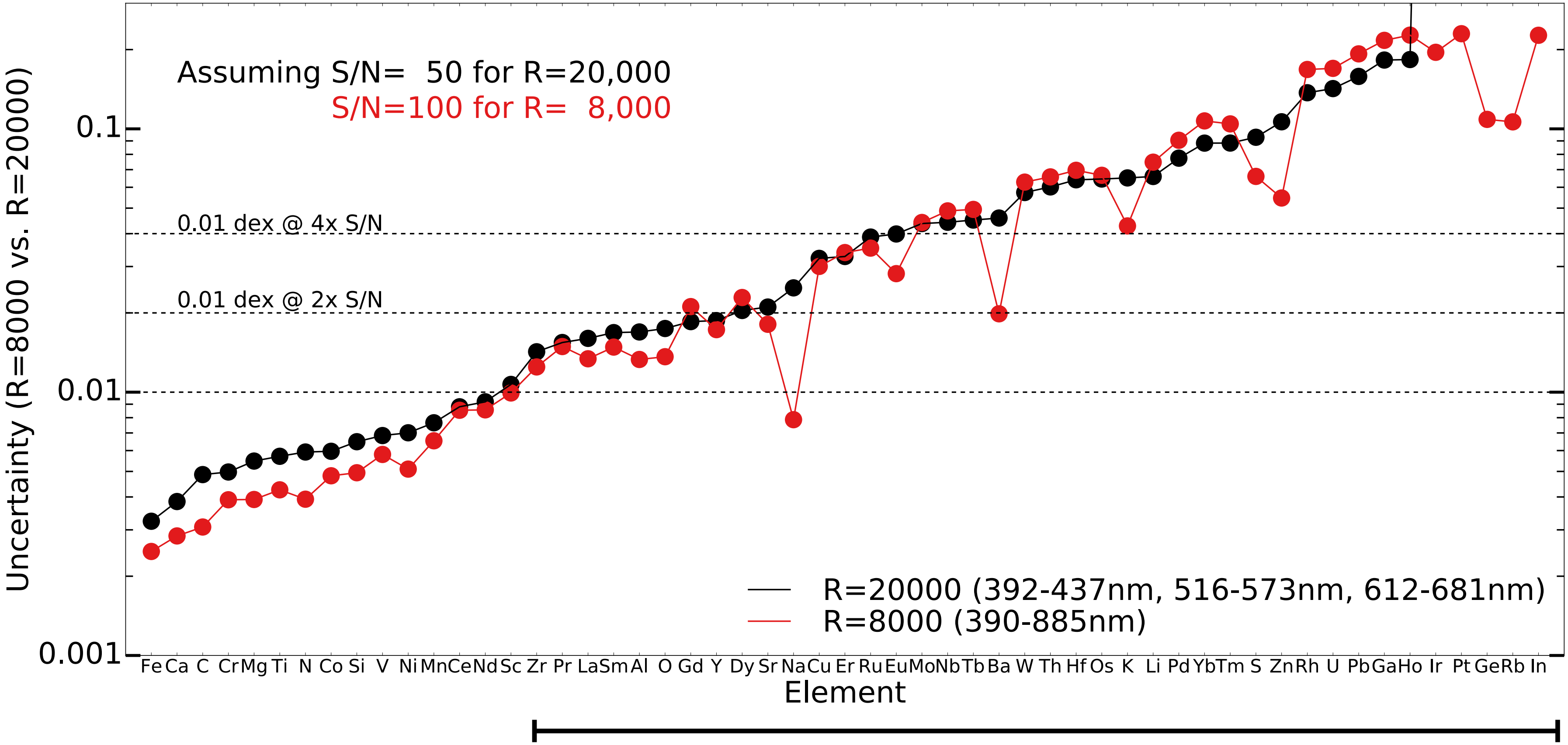


New: extragalactic spectroscopy
of **individual stars**, and **star clusters**
out to 70 Mpc
(Evans et al. 2011)



New techniques

Better statistical models to determine stellar abundances may soon yield way more information on rare-earths



Ting et al. 2016, Rix et al. 2016, Ting et al. in prep

New models

recently, most efforts focus on 3D, NLTE

- ✓ 3D convection simulations
- ✓ Non-local thermodynamic equilibrium

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{v}),$$

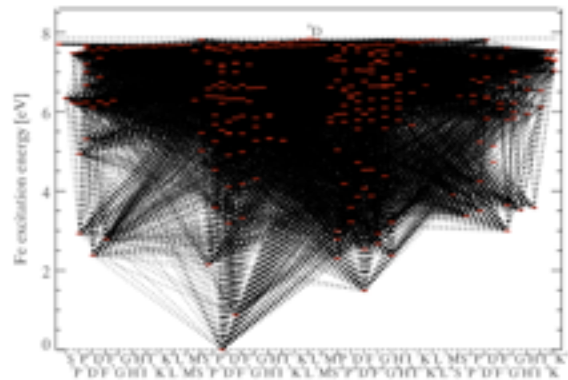
$$\frac{\partial \rho \boldsymbol{v}}{\partial t} = -\nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) - \nabla P - \rho \nabla \Phi - \nabla \cdot \tau_{visc},$$

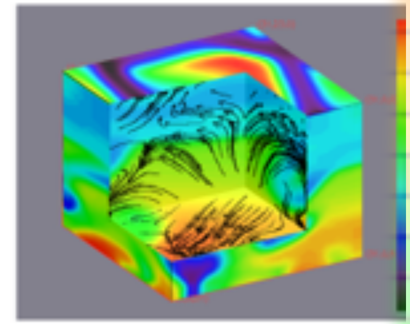
$$\Phi = -\frac{GM}{(r_0^4 + r^4/\sqrt{1} + (r/r_1)^8)^{1/4}}$$

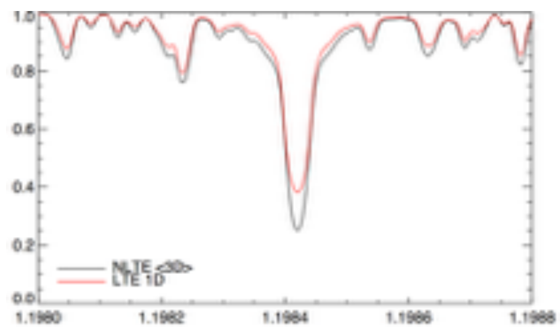
$$\frac{\partial e}{\partial t} = -\nabla \cdot (e \boldsymbol{v}) - P(\nabla \cdot \boldsymbol{v})/\rho + Q_{\rm rad} + Q_{\rm visc}$$

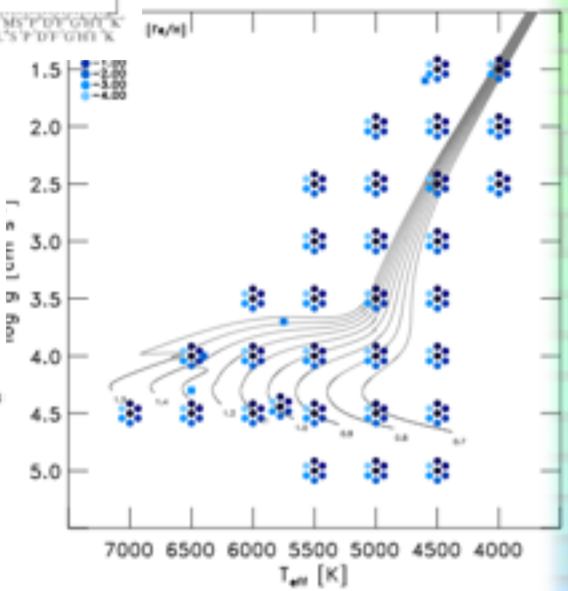
$$Q_{\rm rad} \equiv \sum_{n=1,n_bins} (J_{bin} - B_{bin}) w_{bin},$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial (n_i \upsilon)}{\partial z} = \sum_{j \neq i}^{N} n_j P_{ji} - n_i \sum_{j \neq i}^{N} P_{ij}$$



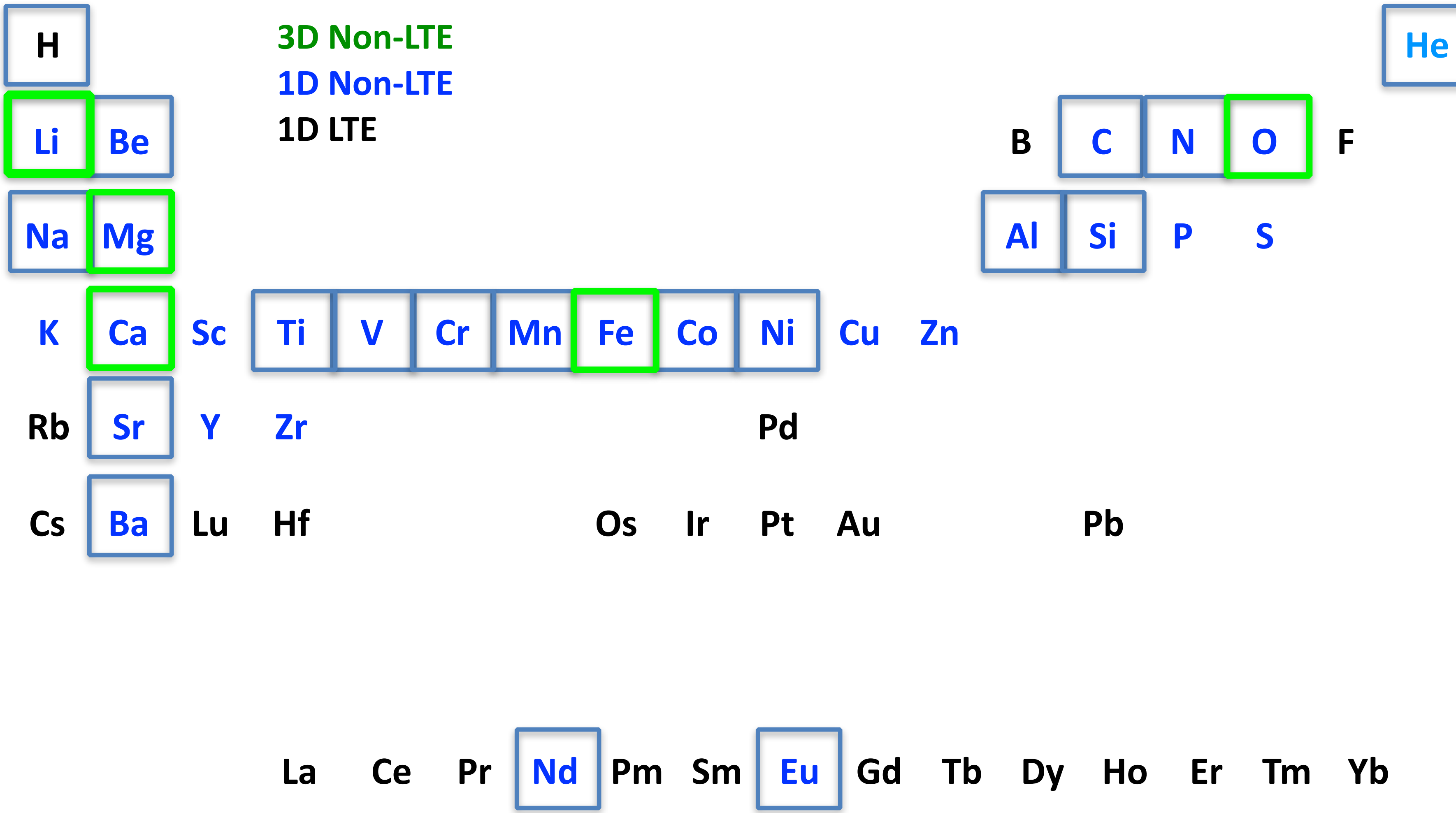




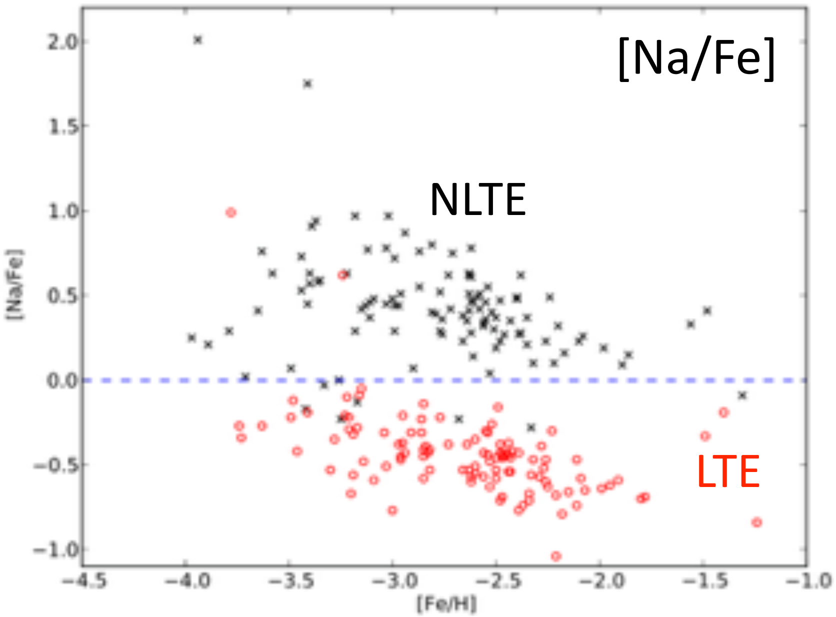


Bergemann+ 2012a,b,c, 2013; Magic+ 2014, Collet+ 2012, Lind+

State-of-the-art

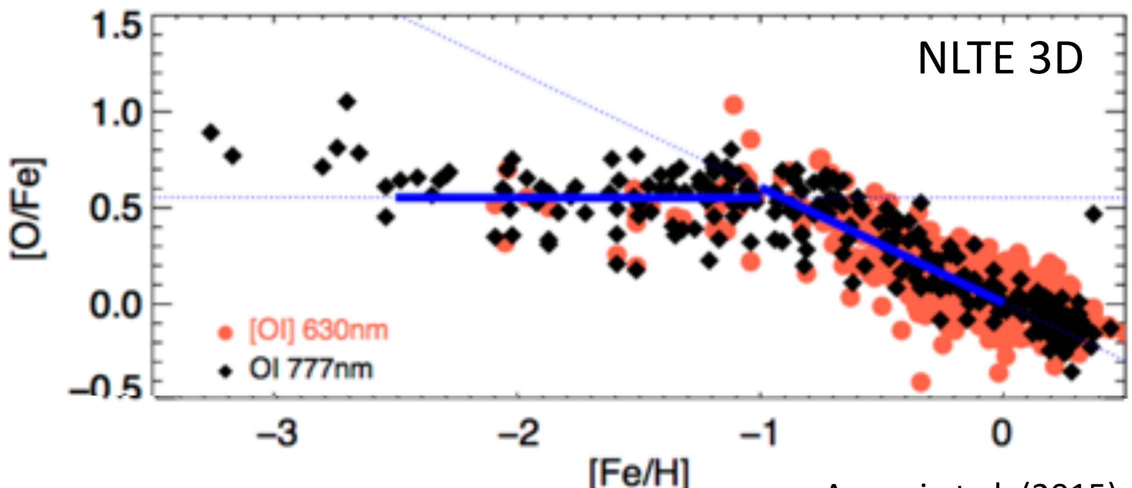


Abundances in Galactic stars



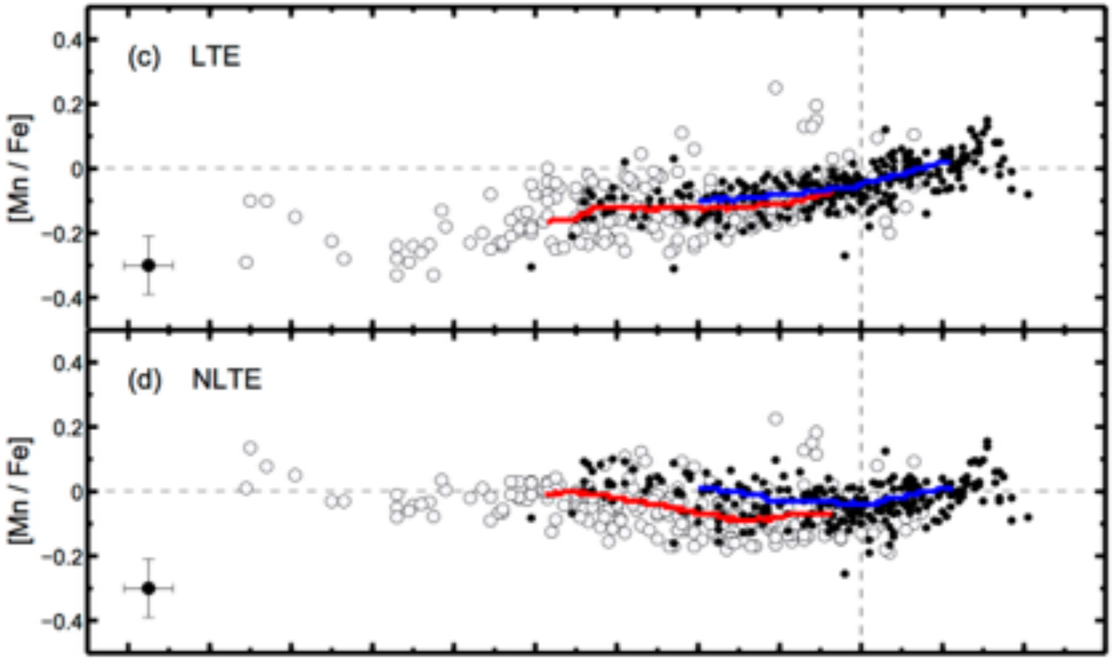
Lind et al. (2011), Jacobson et al. (2015)

[O/Fe]

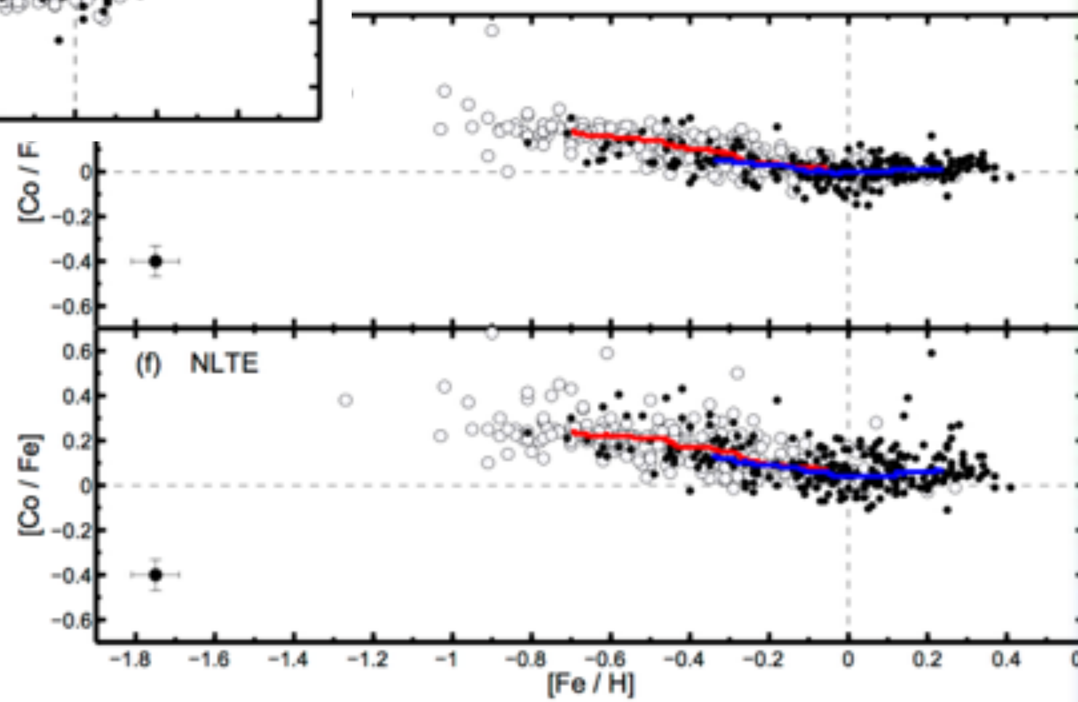


Amarsi et al. (2015)

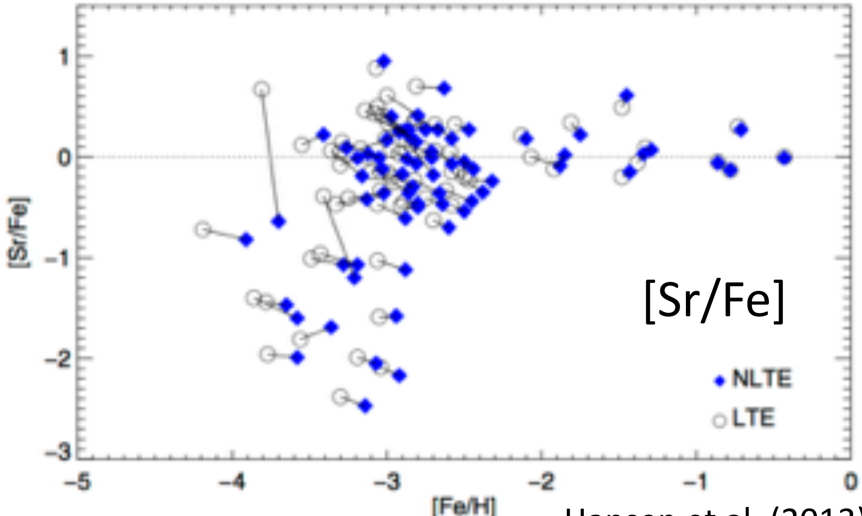
[Mn/Fe]



[Co/Fe]

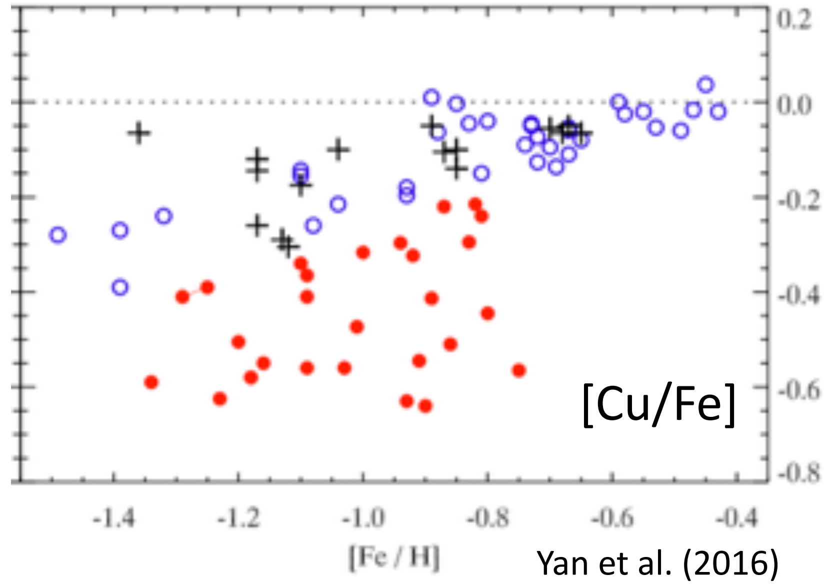


Battistini & Bensby (2015)



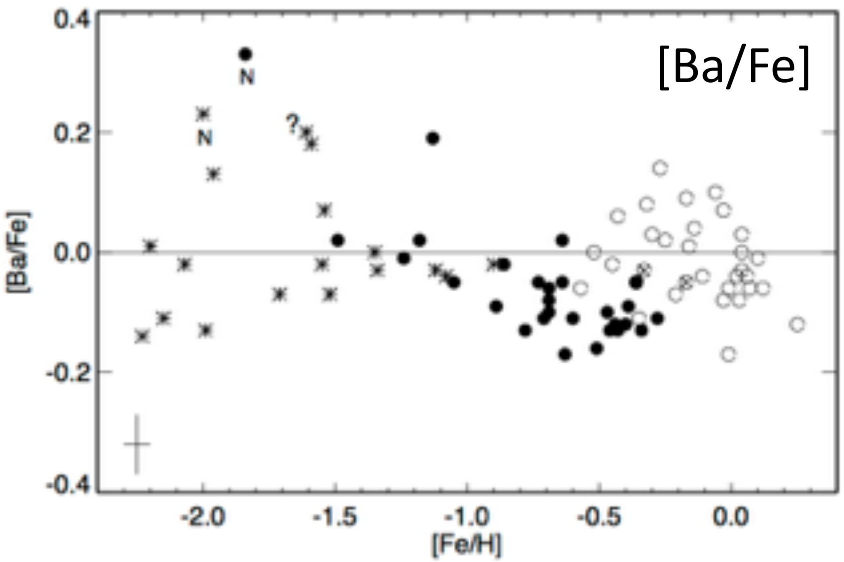
Hansen et al. (2013)

NLTE

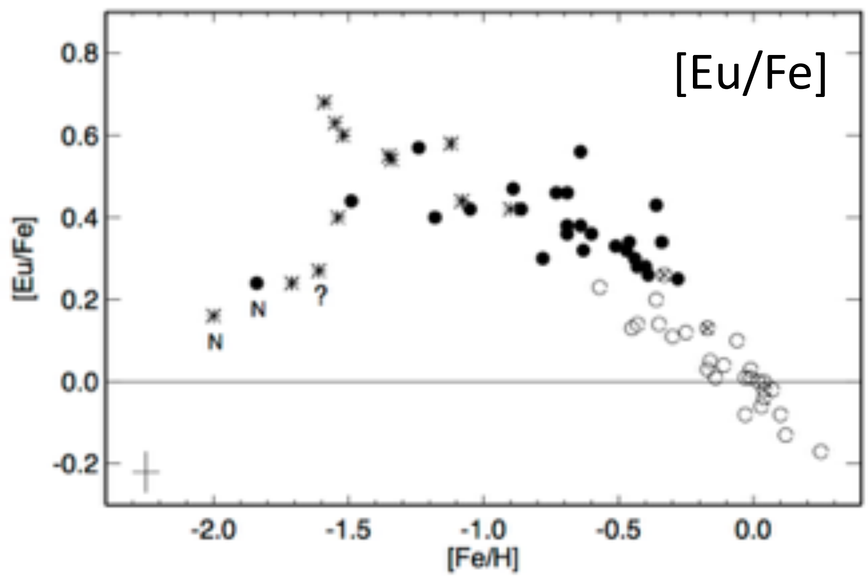


Yan et al. (2016)

NLTE



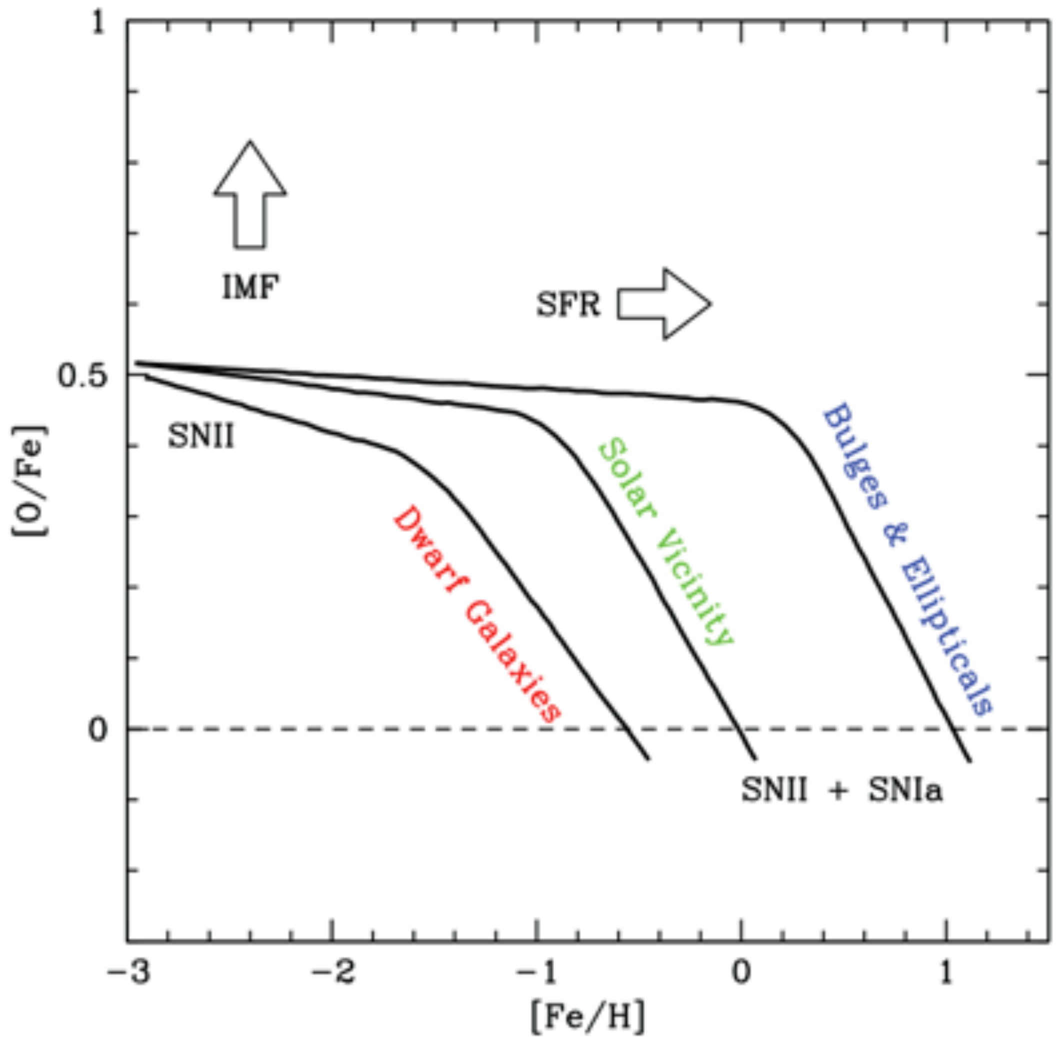
Mashonkina et al. (2003)



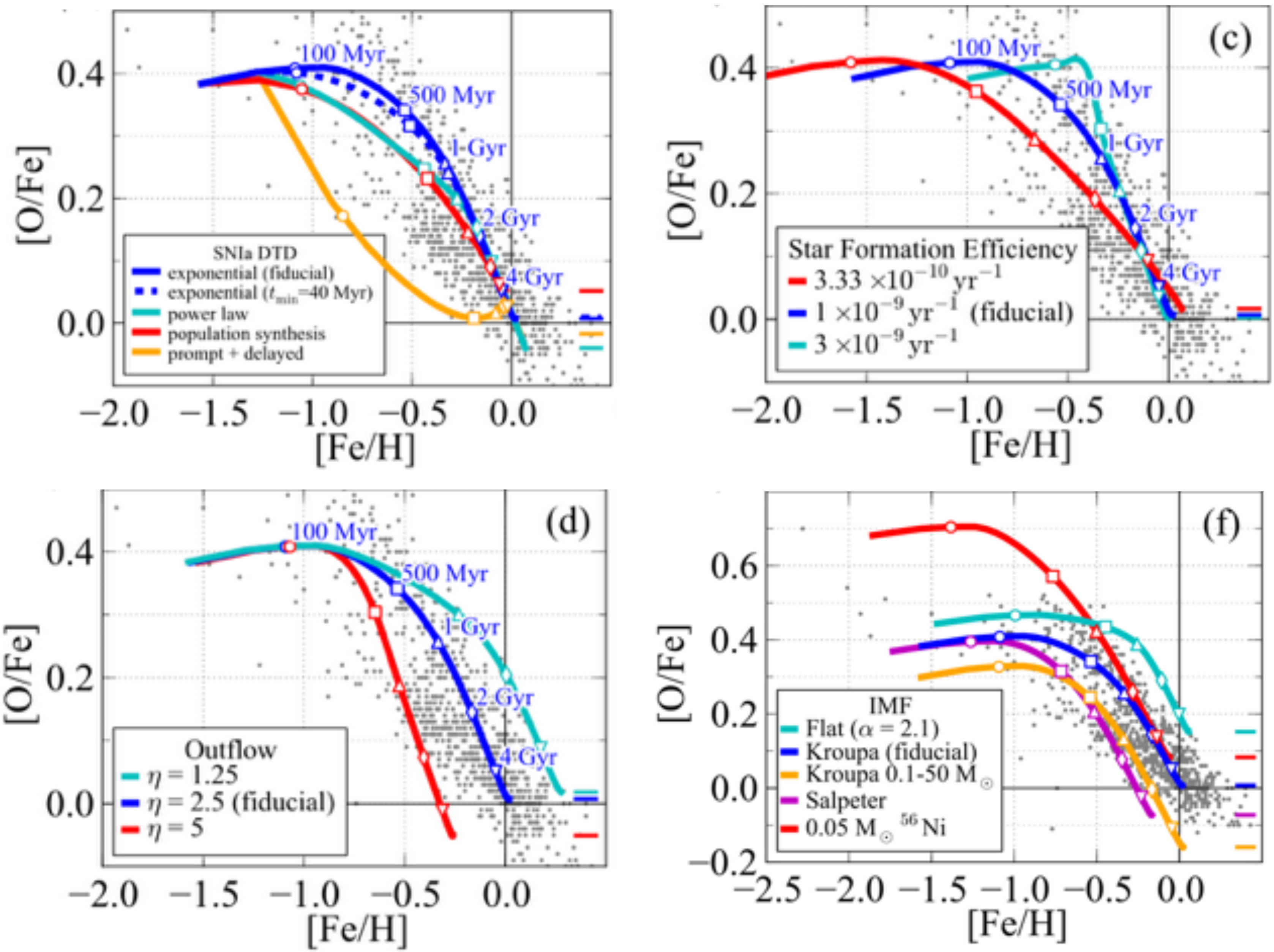
Mashonkina et al. (2003)

Chemical Evolution models for the Milky Way

- initial conditions
- stellar birthrate function
- stellar yields
- gas flows (infall, outflow, radial flow)

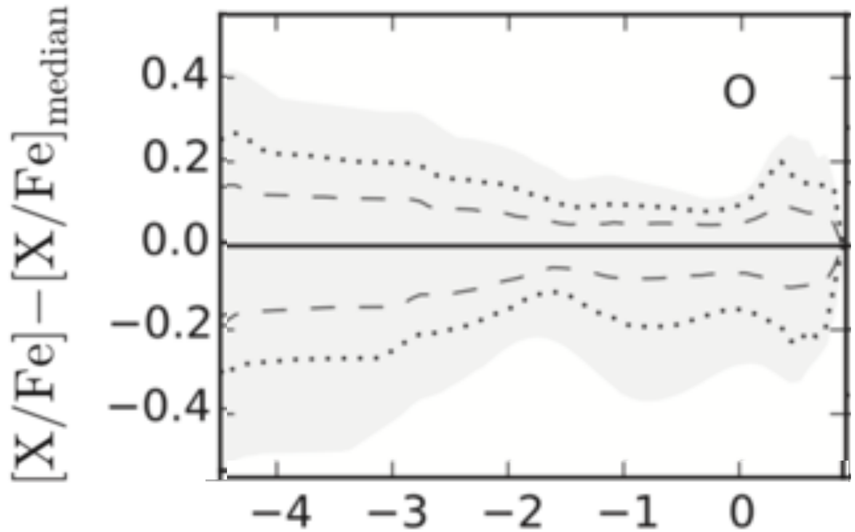


Matteucci & Brocato (1990)



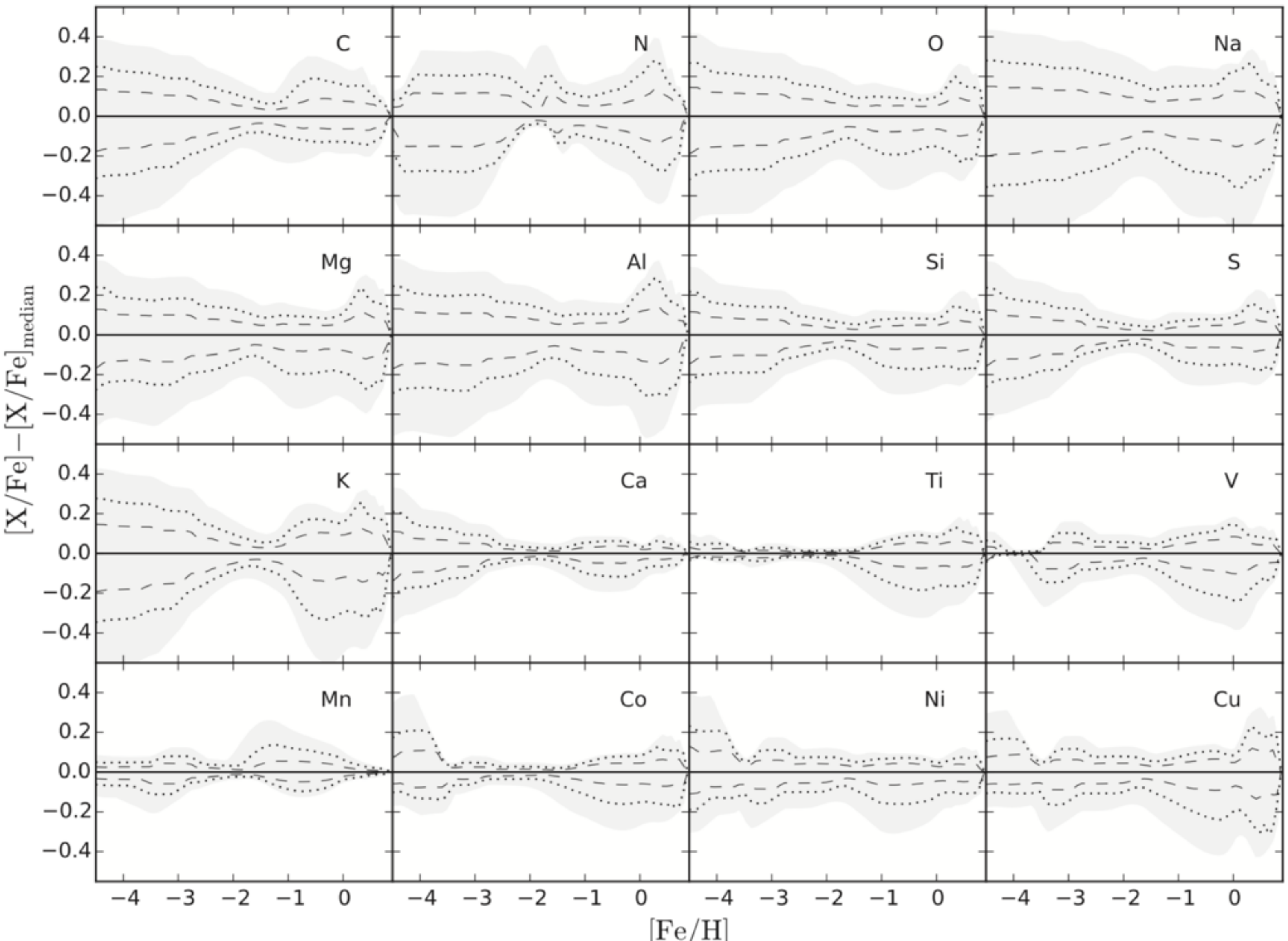
Andrews et al. (2016)

[O/Fe]

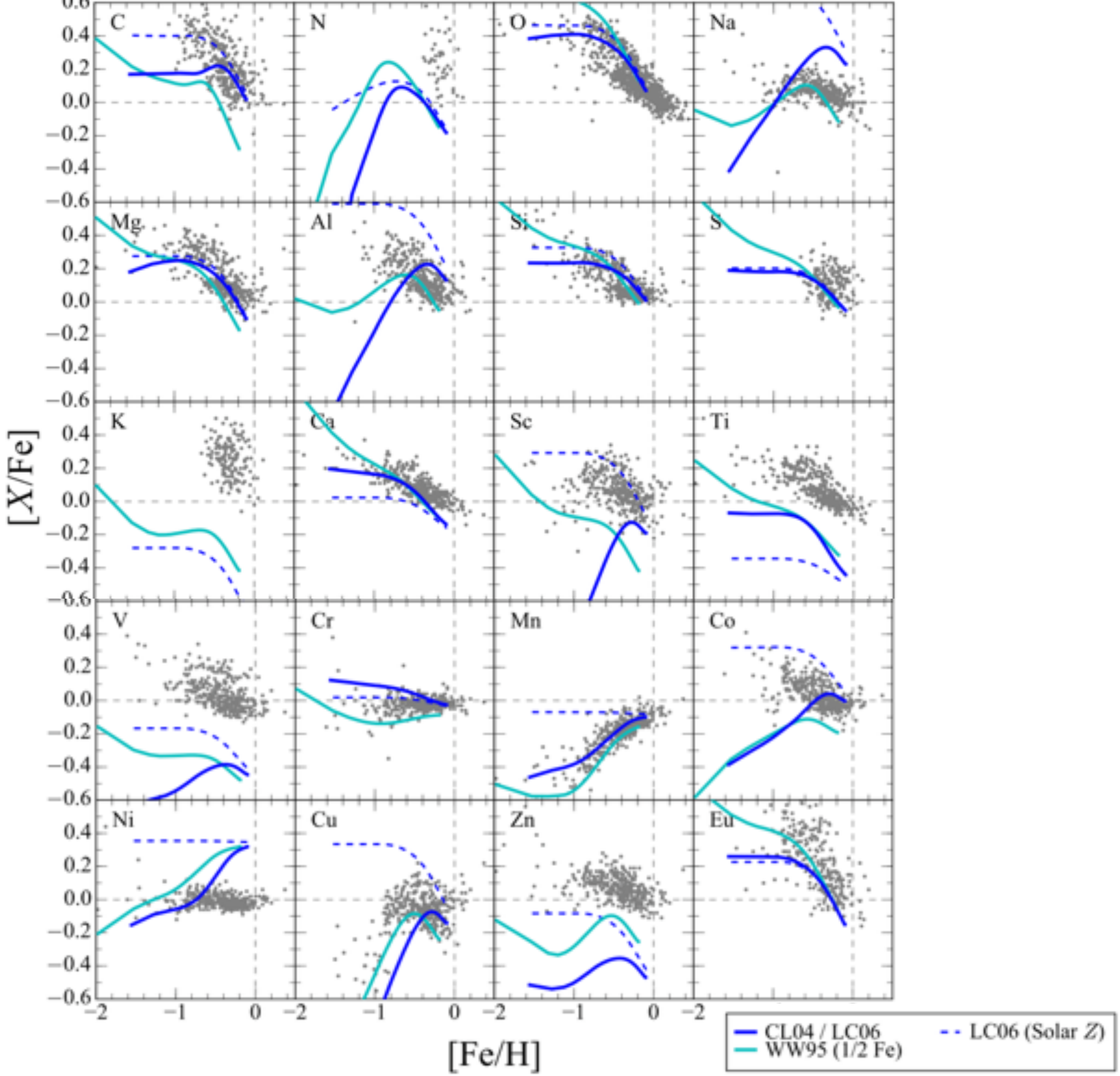


[Fe/H]

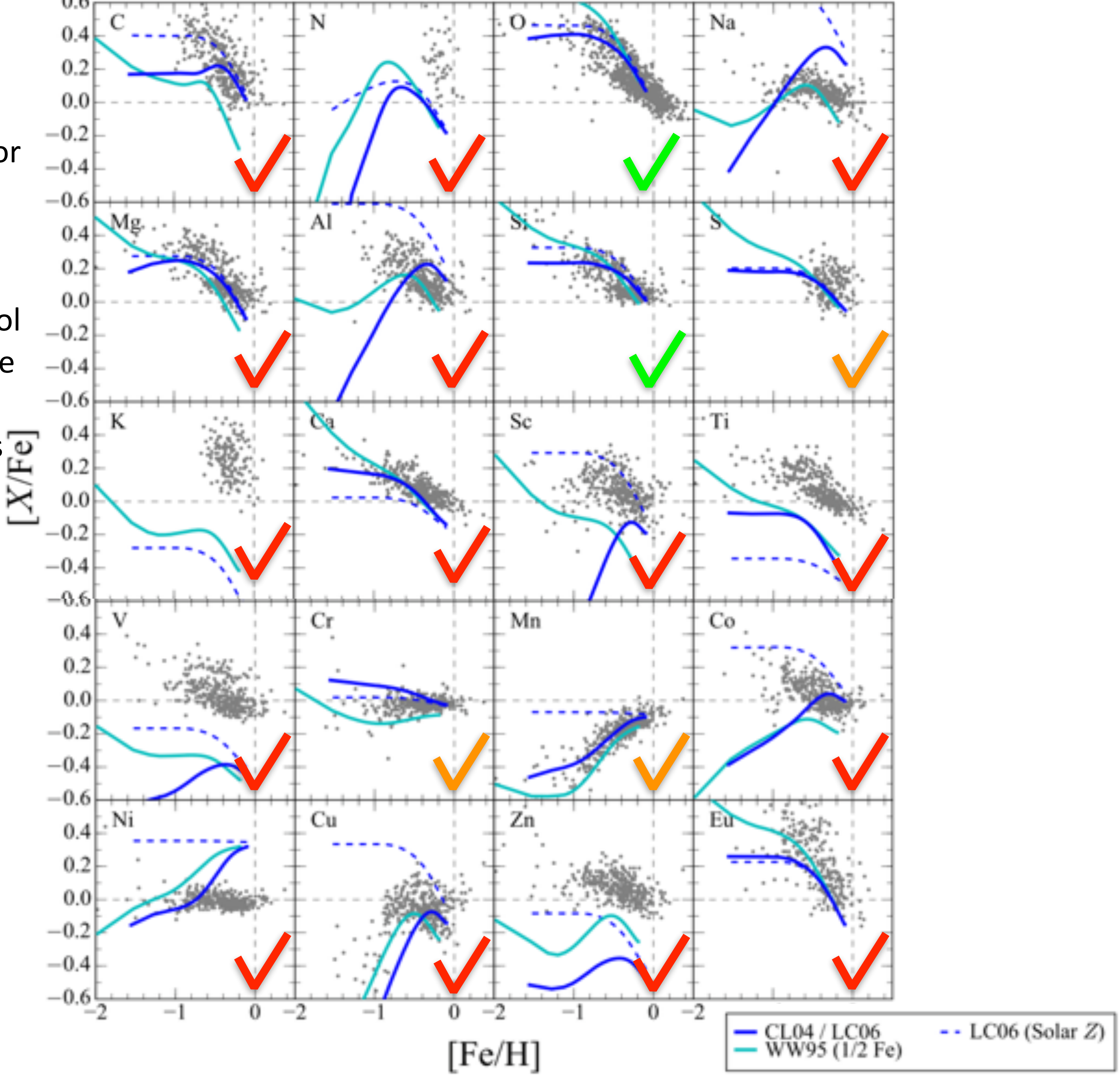
varying other parameters in the chemical evolution models



Côté et al. 2016

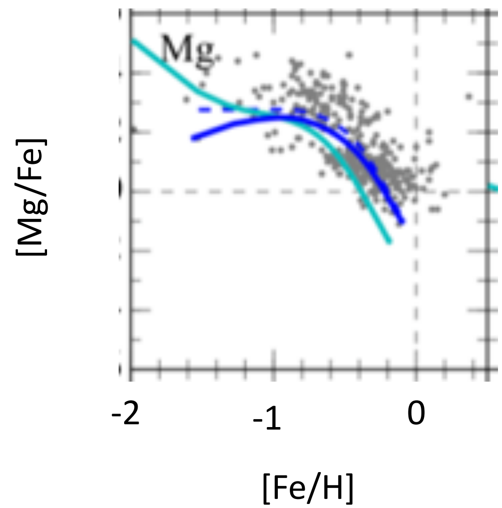

C
N
O
Na
Mg
Al
Si
S
K
Ca
Sc
Ti
V
Cr
Mn
Co
Ni
Cu
Zn
Eu
[X/Fe]
[Fe/H]
CL04 / LC06
WW95 (1/2 Fe)
LC06 (Solar Z)

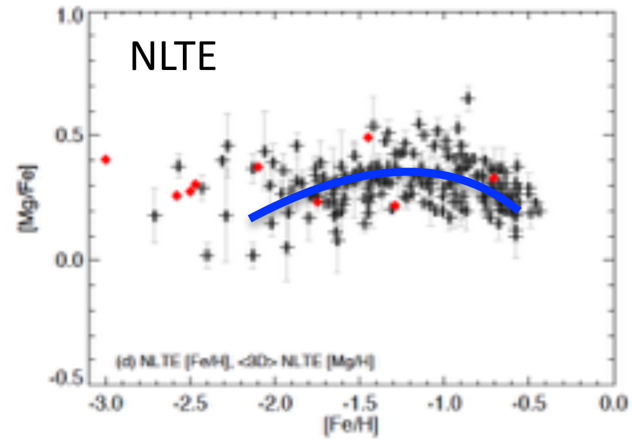
Major disagreement for the most chemical elements measured in cool stars suggest the current nucleosyntheiss yields are incomplete.



Successes

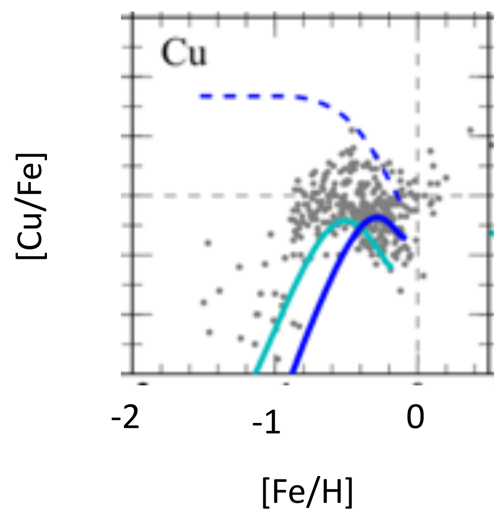
- Magnesium

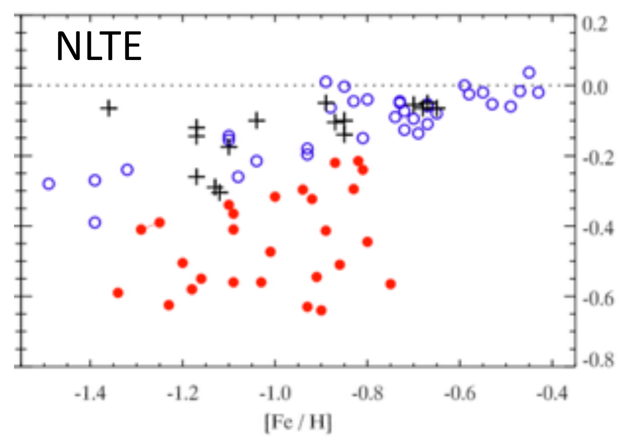




Bergemann et al. (2016b, subm.)

- Copper



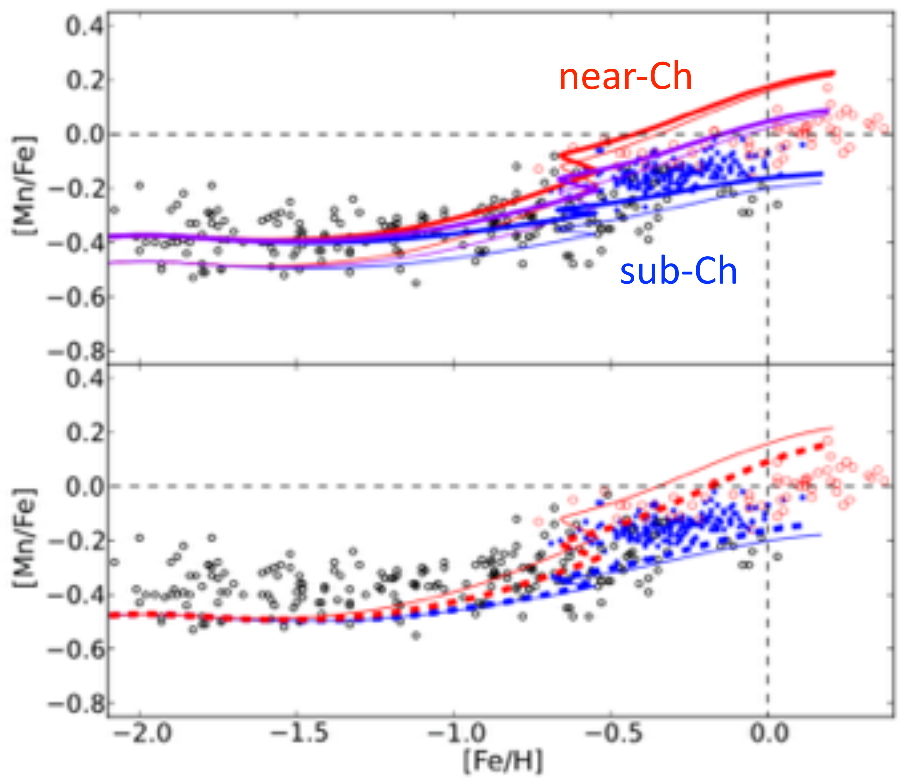


Yan et al. (2016)

Manganese

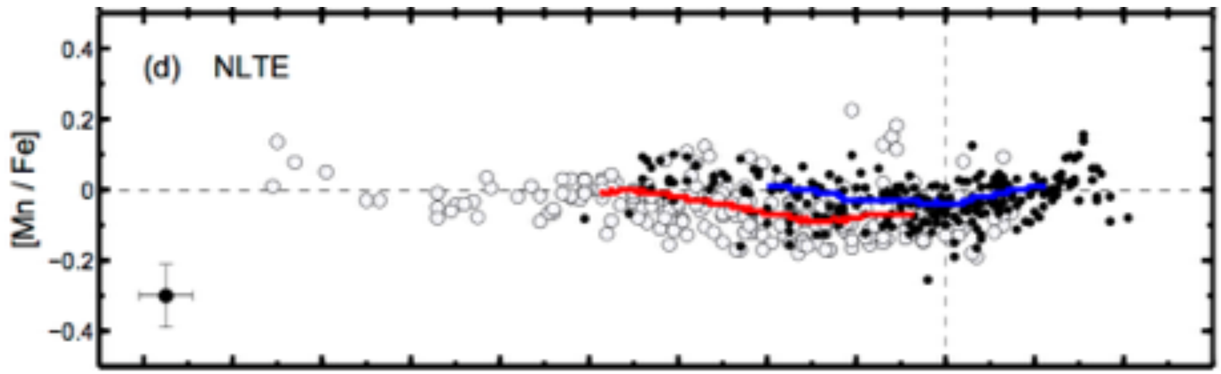
- observationally challenging: hyperfine splitting
- strong non-local thermodynamic equilibrium effects
- but excellent observational databases

- consistency check for the SNIa DTD?
- SN II underproduce Mn I at all metallicity
  WW95 : Z-dependent yields
- Chandrasekhar-mass SN Ia models (Fink et al. 2014): enhanced [Mn/Fe] ~0.3 dex
- Sub-Chandrasekhar-mass SN Ia models (Woosley & Kasen 2011, Seitenzahl et al. 2013): deficient [Mn/Fe] but increases with [Fe/H]

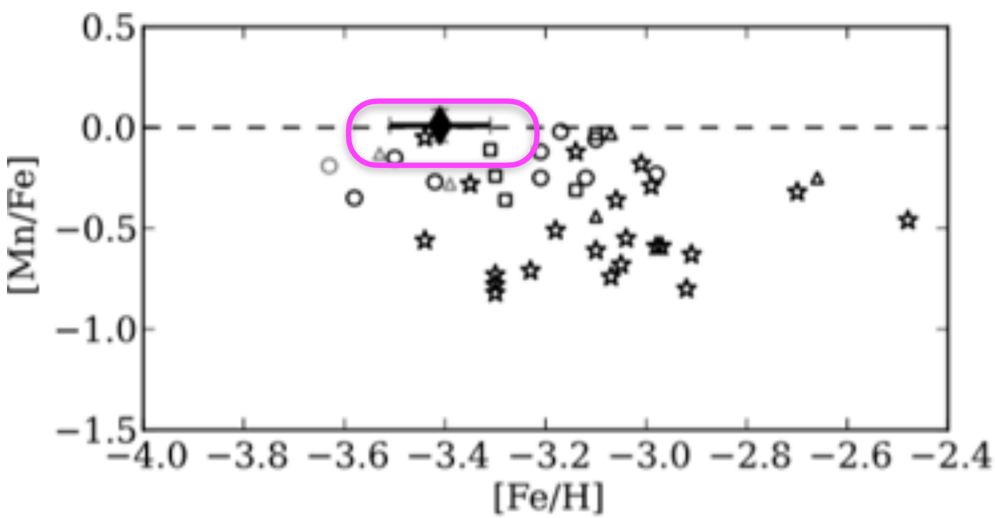


Seitenzahl et al. (2013)

Manganese



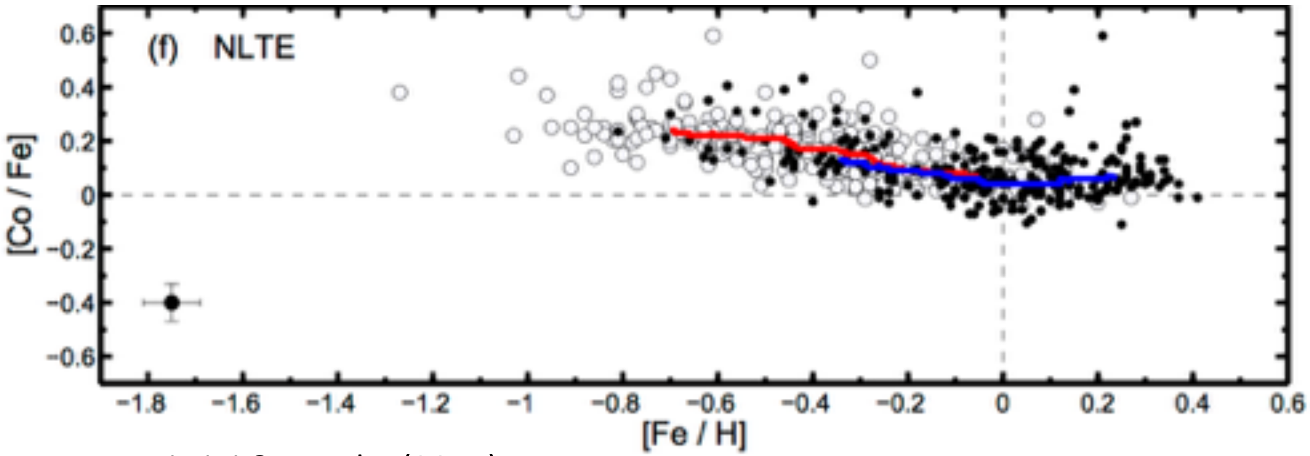
Battistini & Bensby (2015)



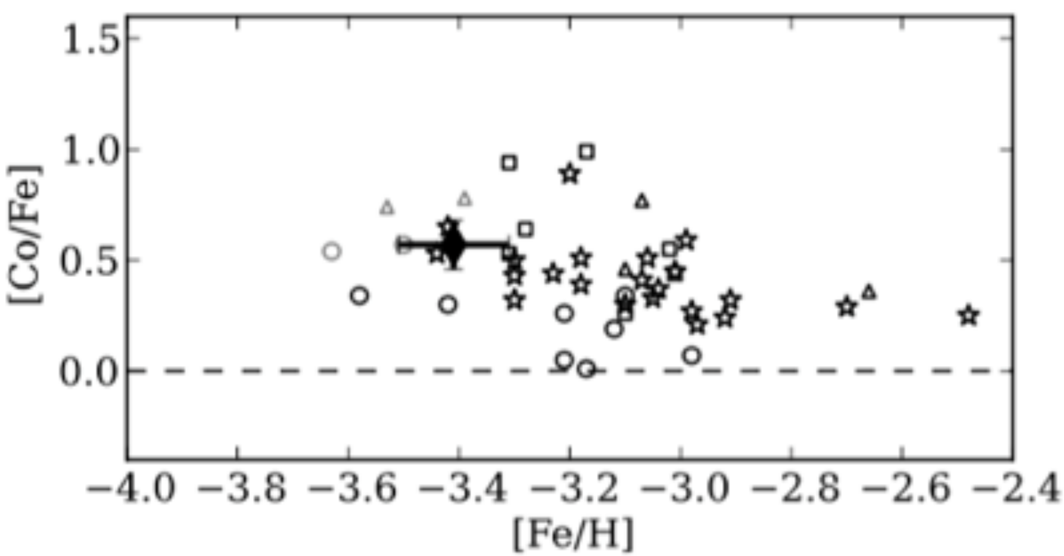
Jacobson & Frebel (2016)

- NLTE [Mn/Fe] trend is <u>flat at the solar value</u> for all metallicities
- NLTE abundances in very metal-poor stars (Jacobson & Frebel 2016) confirm solar [Mn/Fe] and strong differental NLTE effect
- is consistent with sub-Ch models, and the SNIa time-delay —> SNII yields are in question

Cobalt

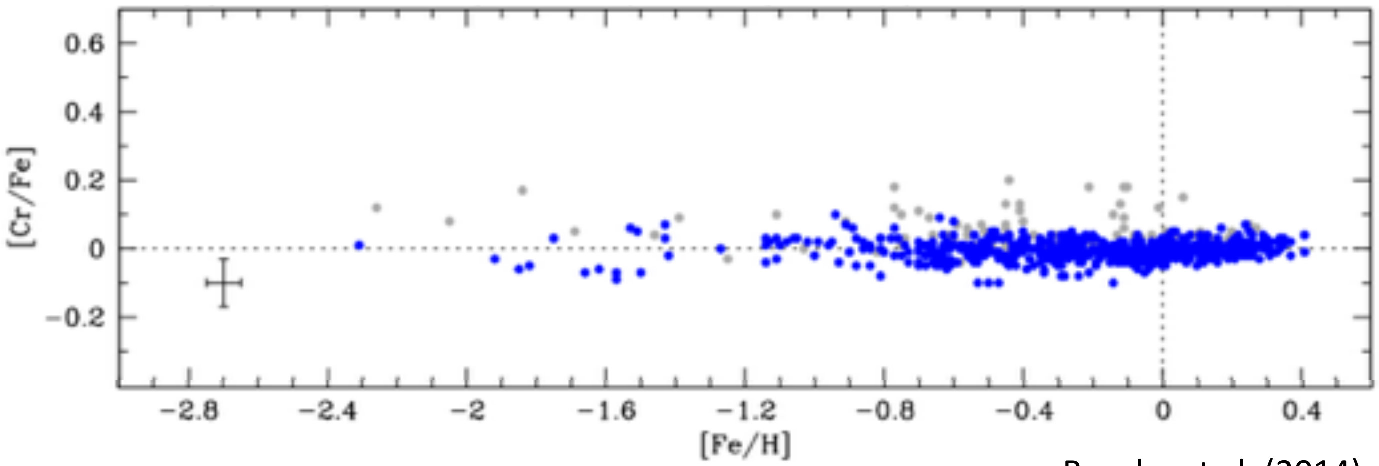


Battistini & Bensby (2015)

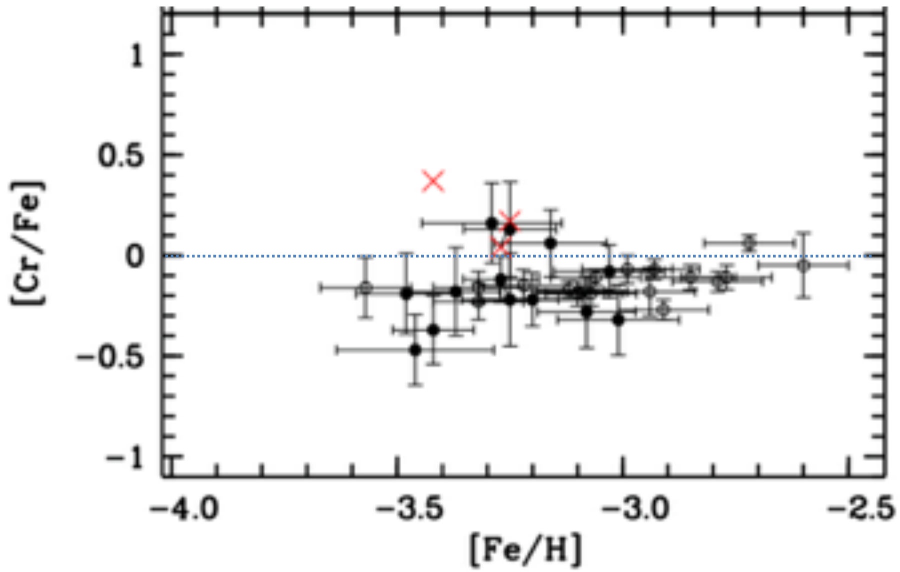


Jacobson & Frebel (2016)

Chromium

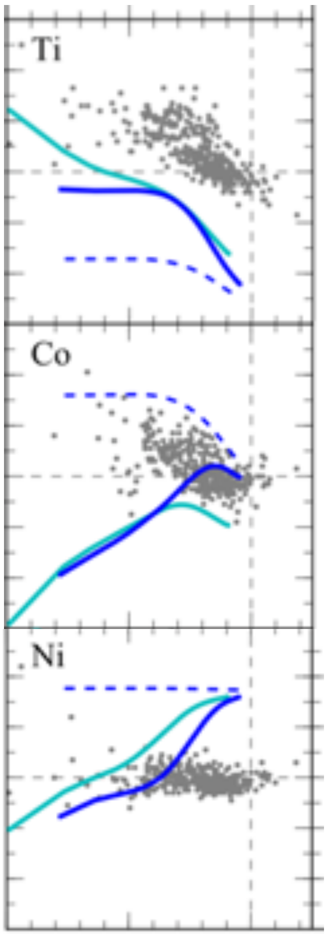


Bensby et al. (2014)



Bonifacio et al. (2012)

The main challenges and questions



- N, Na, Mg, K, Ti, V, Ni and Zn are not produced in quantities appropriate to the solar abundance in any CCSN and SNIa model (offsets 0.2 to 0.5 dex)
- Chemical evolution models do not describe the observed abundance ratios for most chemical elements:
  - main problems for elements produced in explosion (K, Sc, Ti, V, Mn, Co, Ni); also C,N
  - low-[Z]: need for an additional nuclesynthesis channel ? Na, Al, Zn
- The next major step: elements with similar nucleosynthetic origin (Fe-peak — Ti, Mn, Co, Ni)