3D NLTE abundance of iron-peak and neutron-capture elements within GCE context

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Observational constraints on the origin of the elements. IX. 3D NLTE abundances of metals in the context of Galactic Chemical Evolution models and 4MOST

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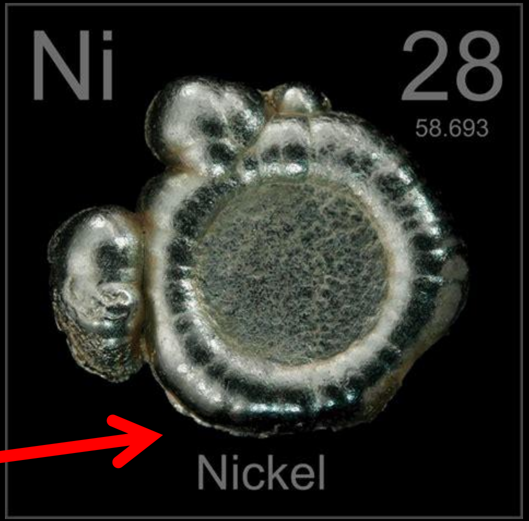

Nickel element

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This conference

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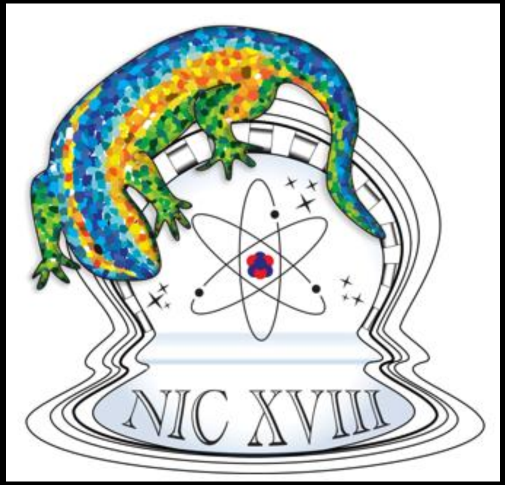

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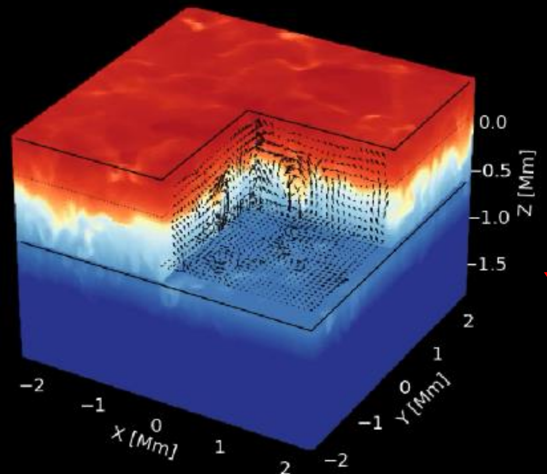

3D model atmospheres

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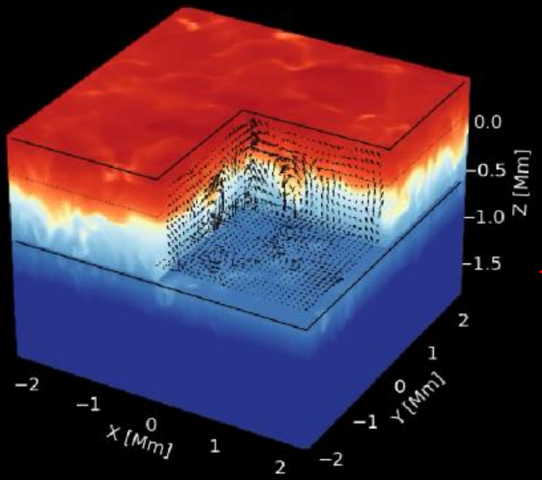

3D model atmospheres

Nickel element

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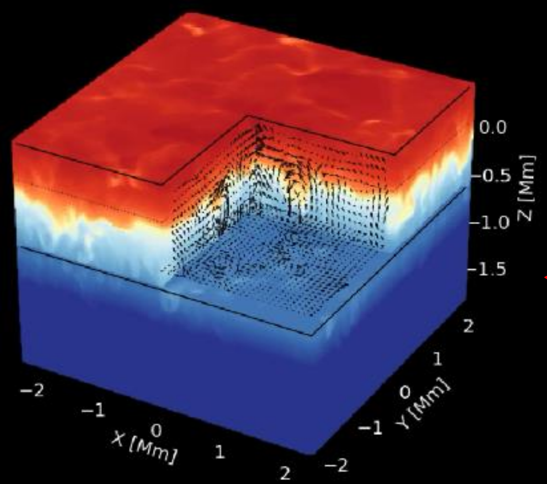

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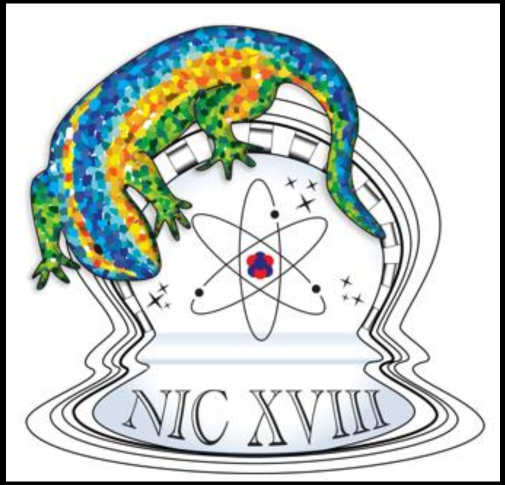

GCE models

- Standard Galactic Chemical Evolution (GCE) models

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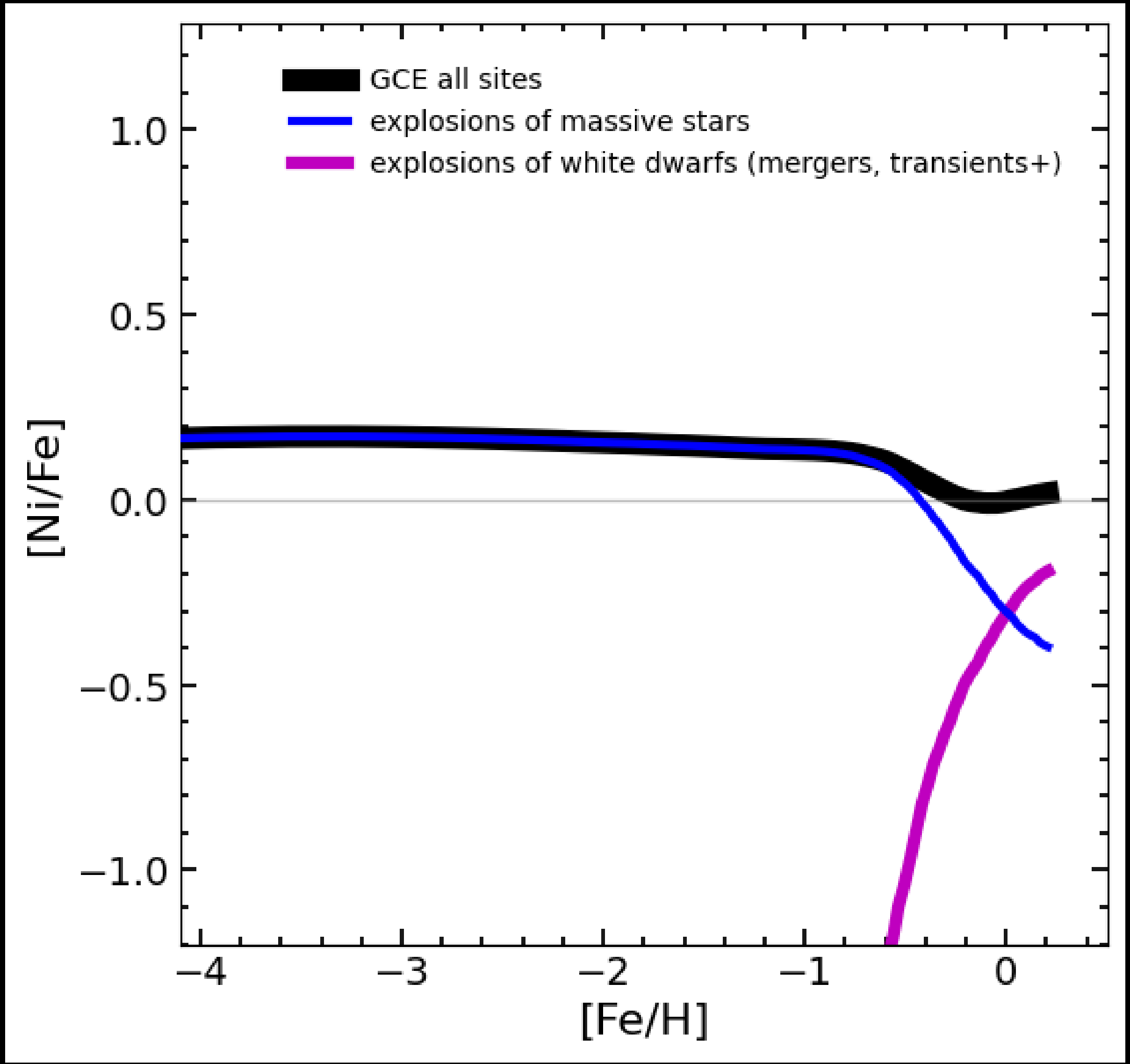

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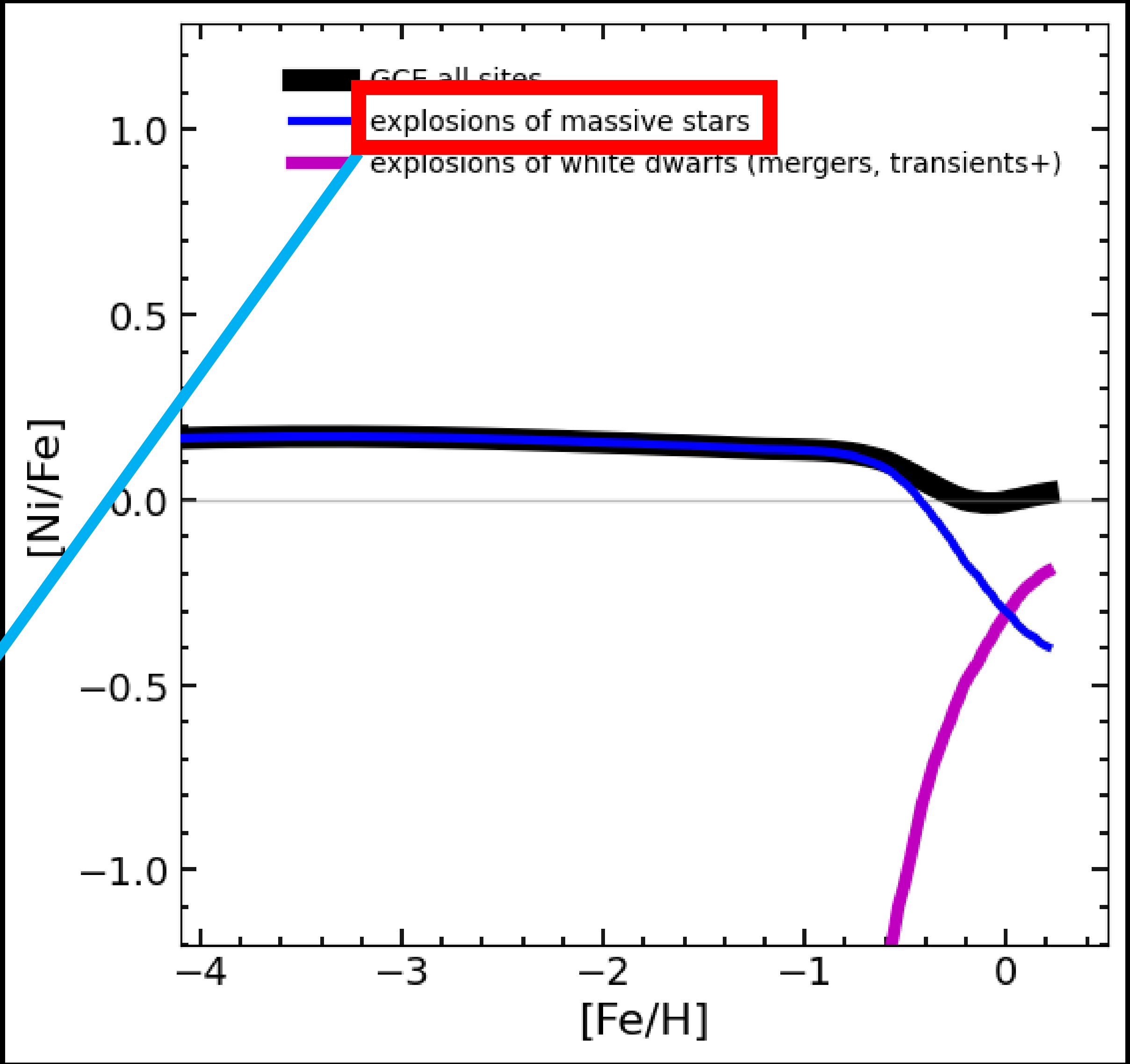

Massive star supernovae, earlier in the galaxy

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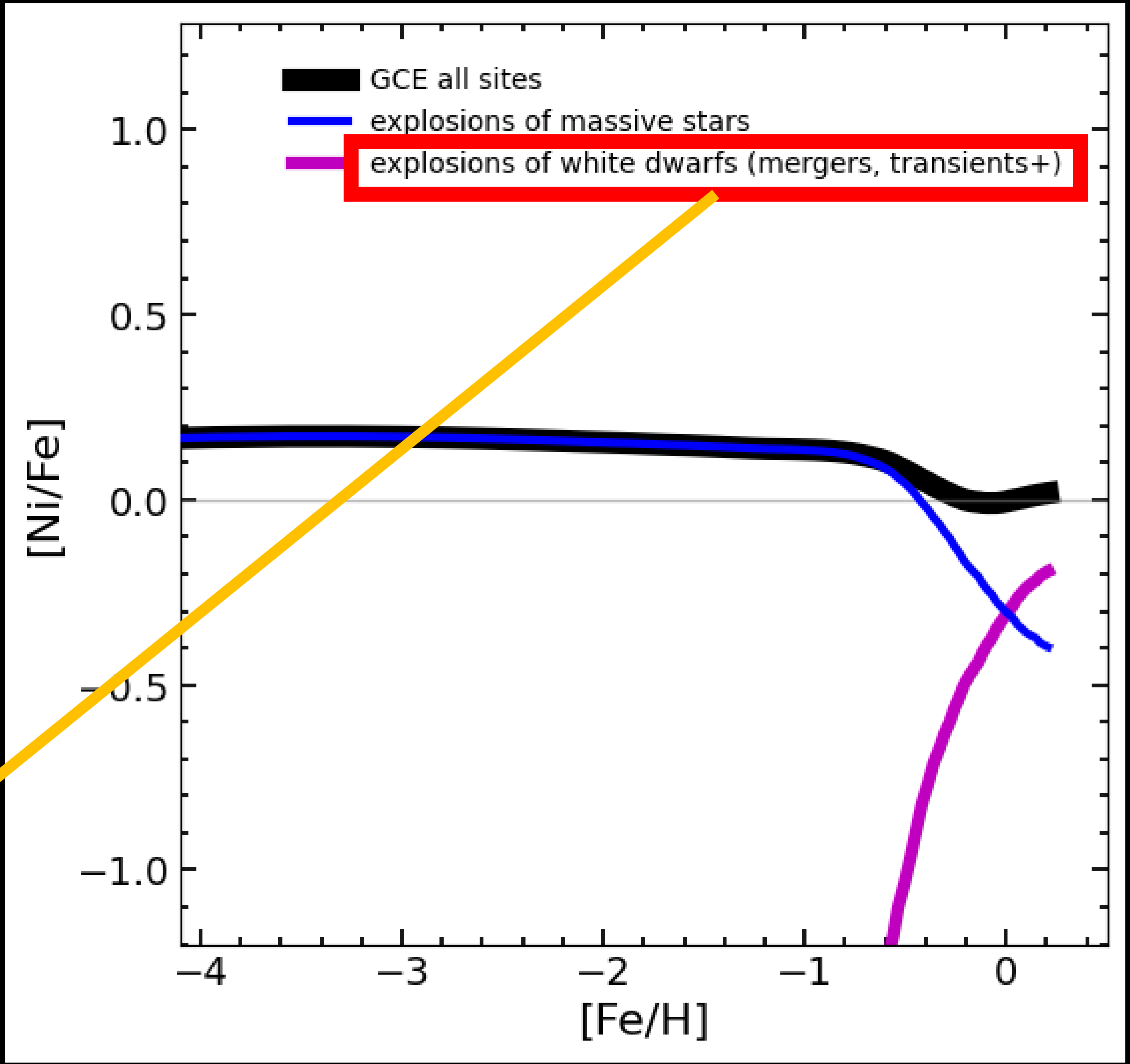

Supernovae Type Ia of white dwarfs in binaries, later in the galaxy

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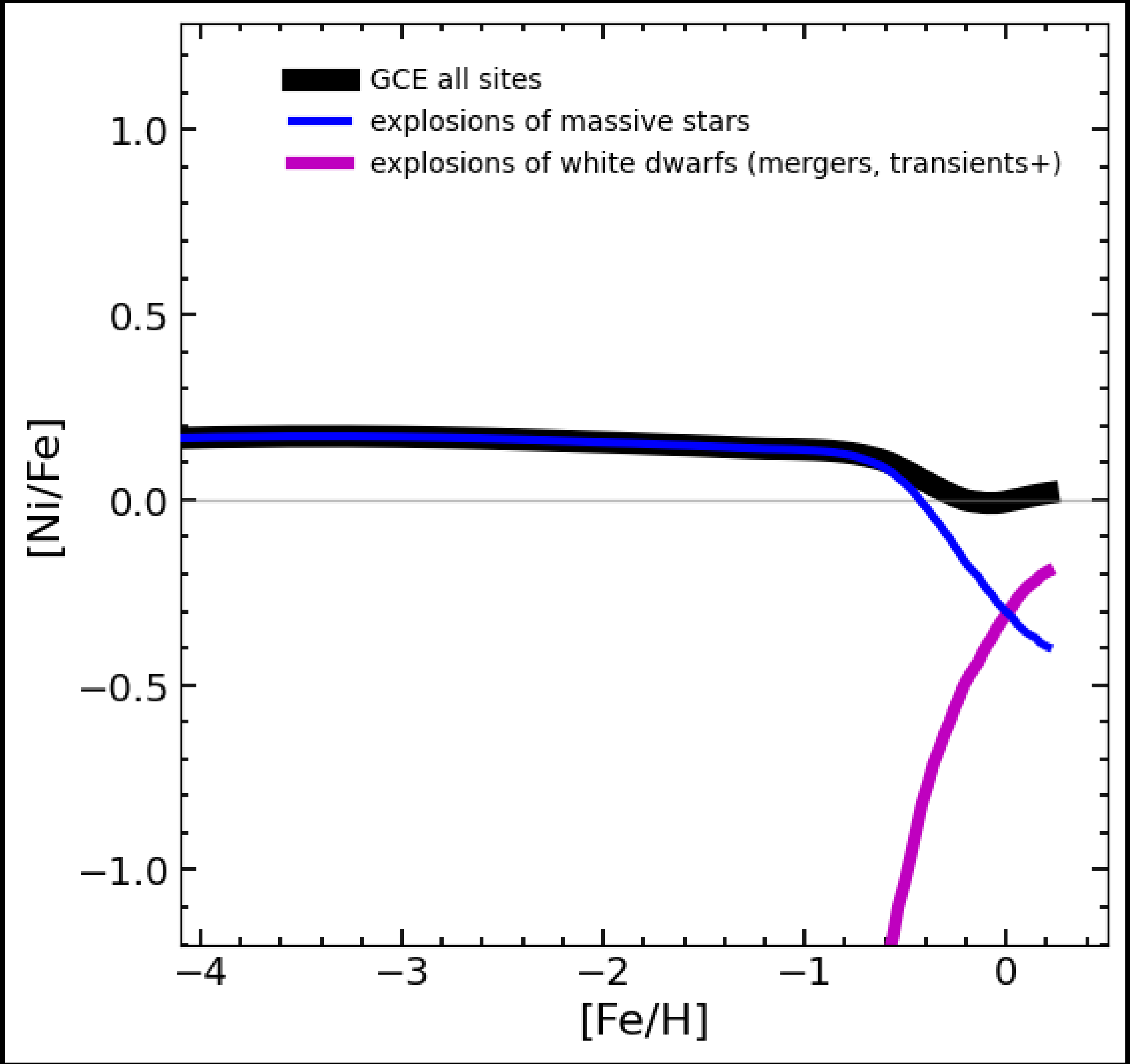
- [X/Fe] vs [Fe/H] -> Fe is important
  - Need to understand iron-peak production



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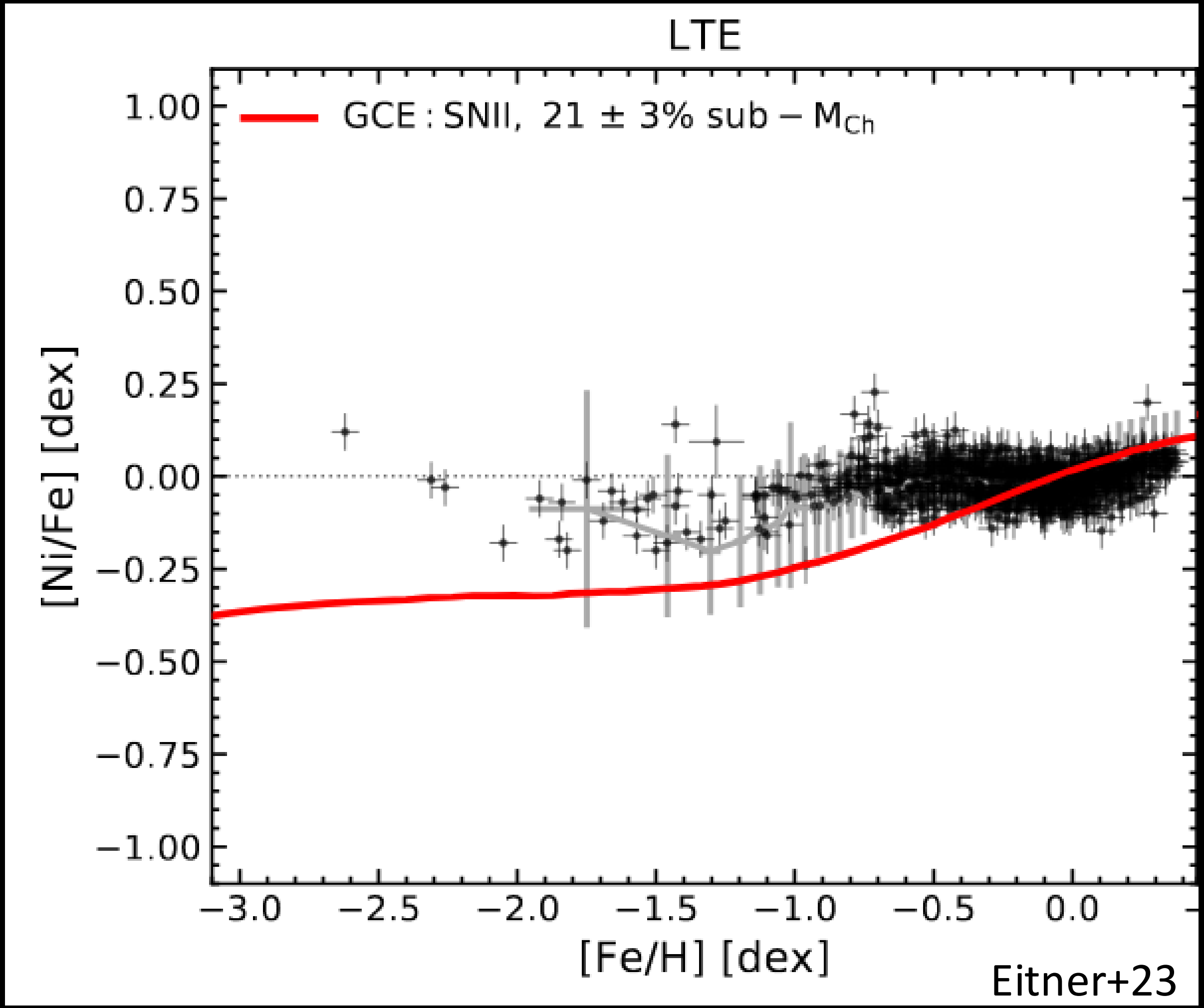

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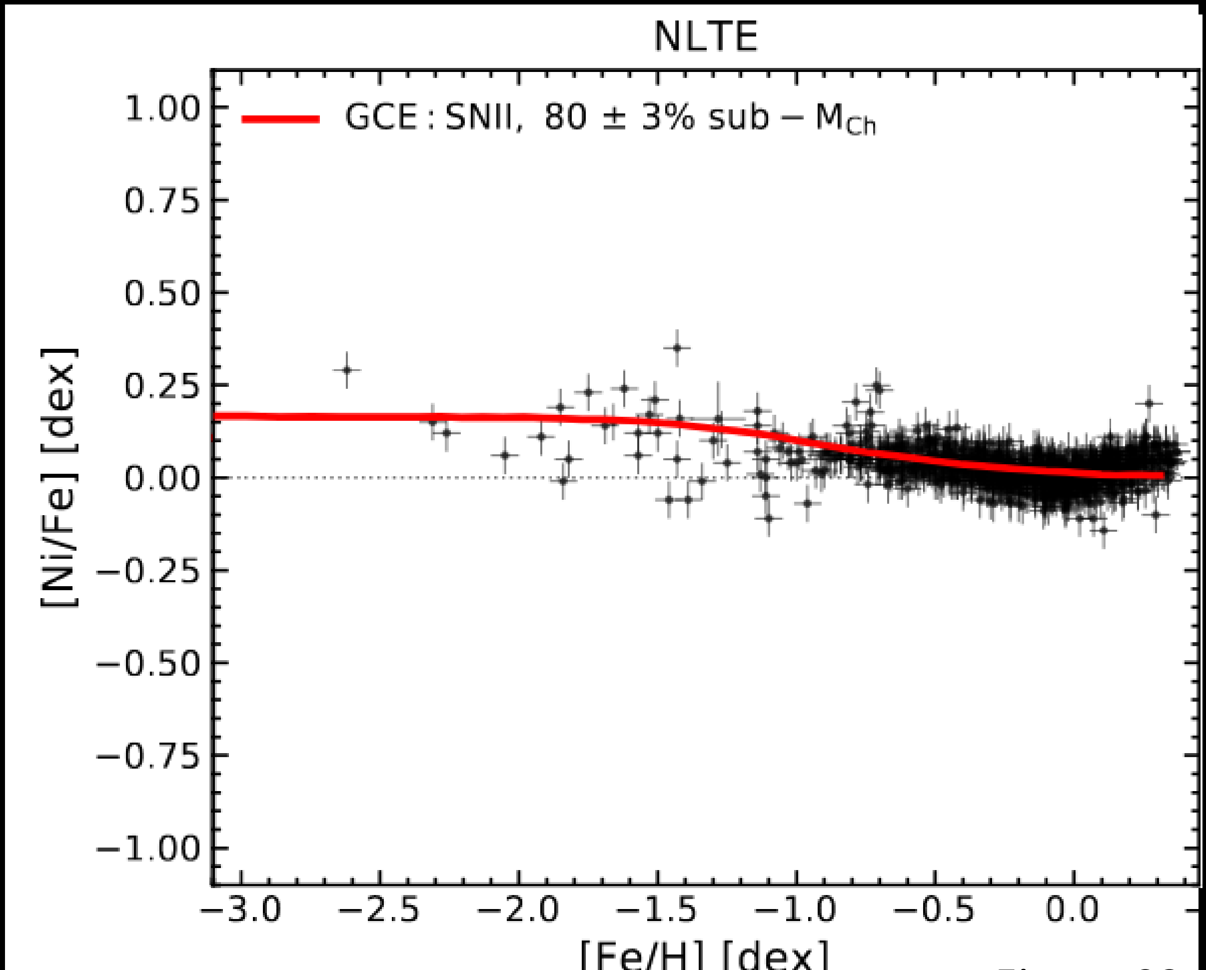
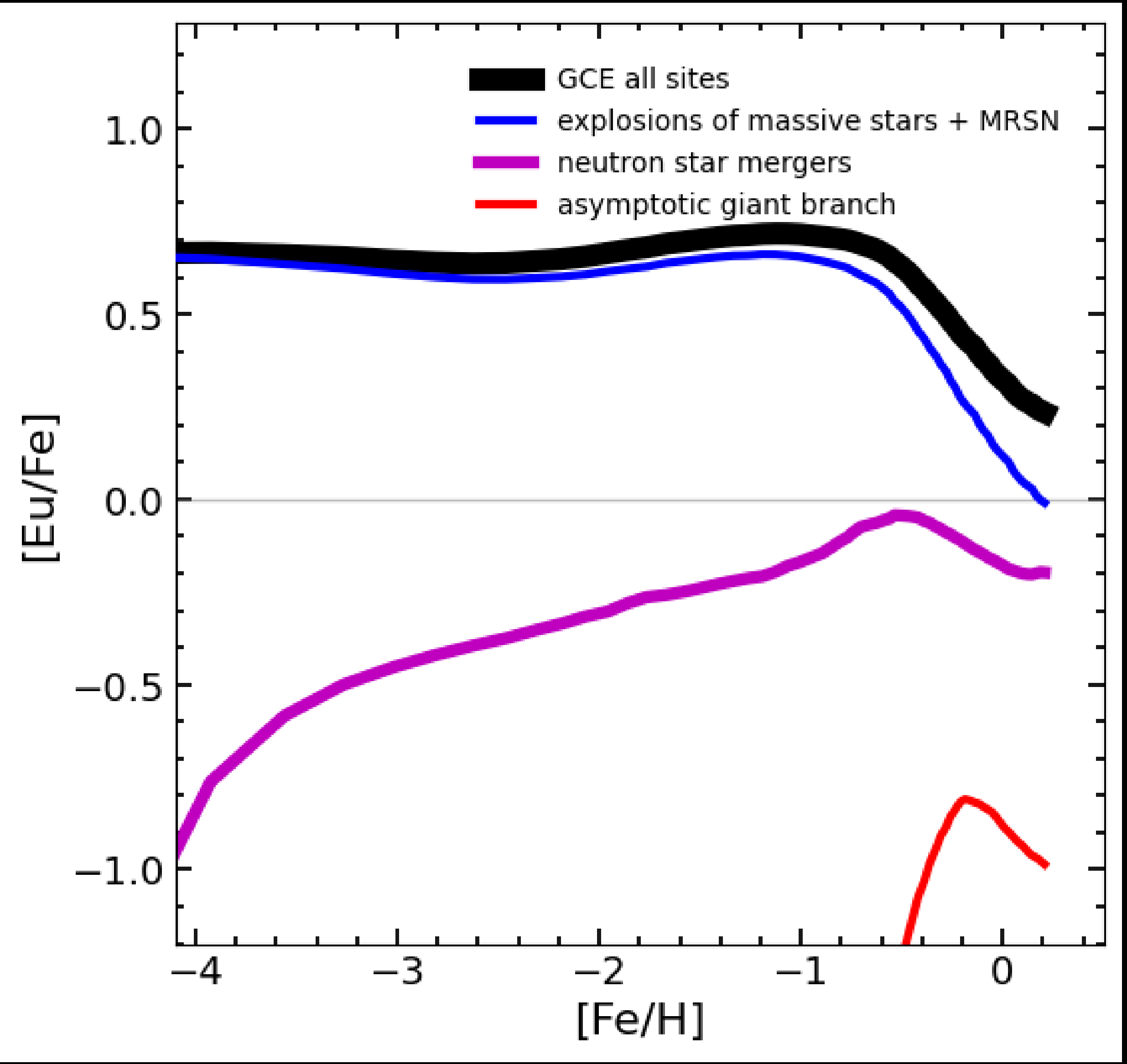
  - NLTE: changes GCE model understanding



Eitner+23

GCE models

- Standard Galactic Chemical Evolution (GCE) models
- [X/Fe] vs [Fe/H] -> Fe is important
  - Need to understand iron-peak production
  - NLTE: changes GCE model understanding
- Neutron-capture elements
  - Slow (s-) and rapid (r-) processes
  - Sites with high neutron densities



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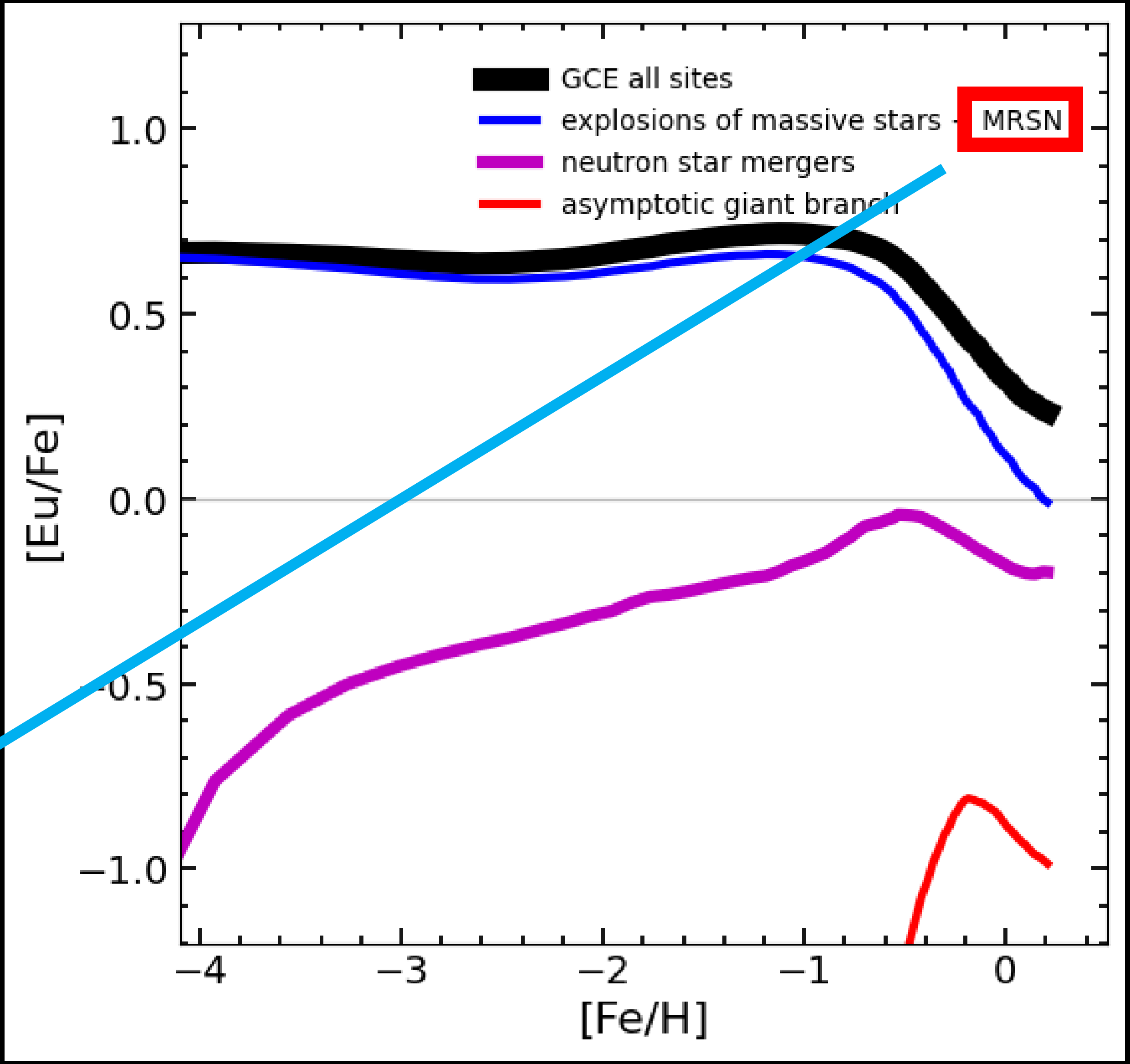

Magnetorotational SNe –
Rare type of CCSN where magnetic and rotational effects play an important role

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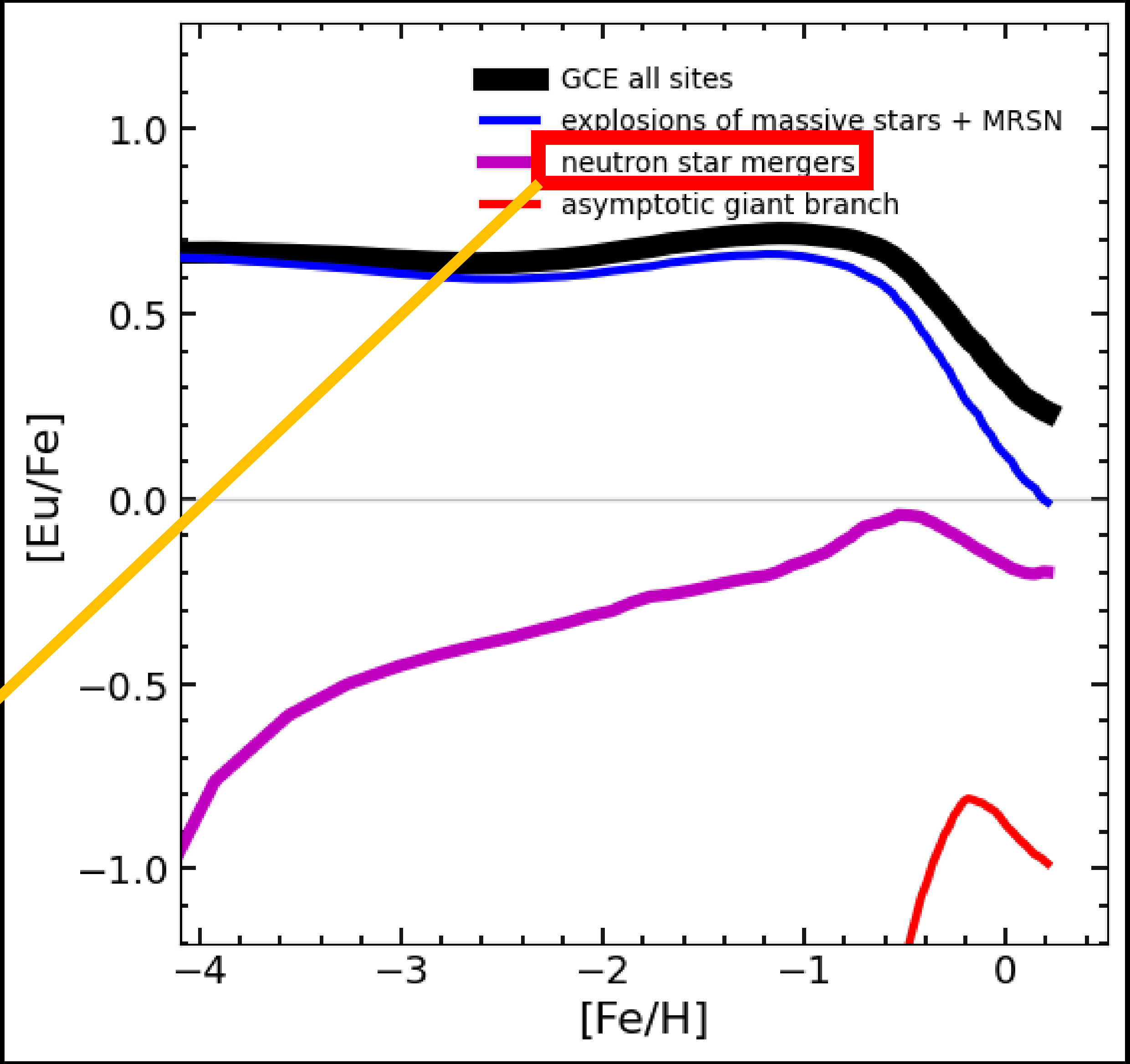
NSM mergers –
r-process site, later in galaxy?



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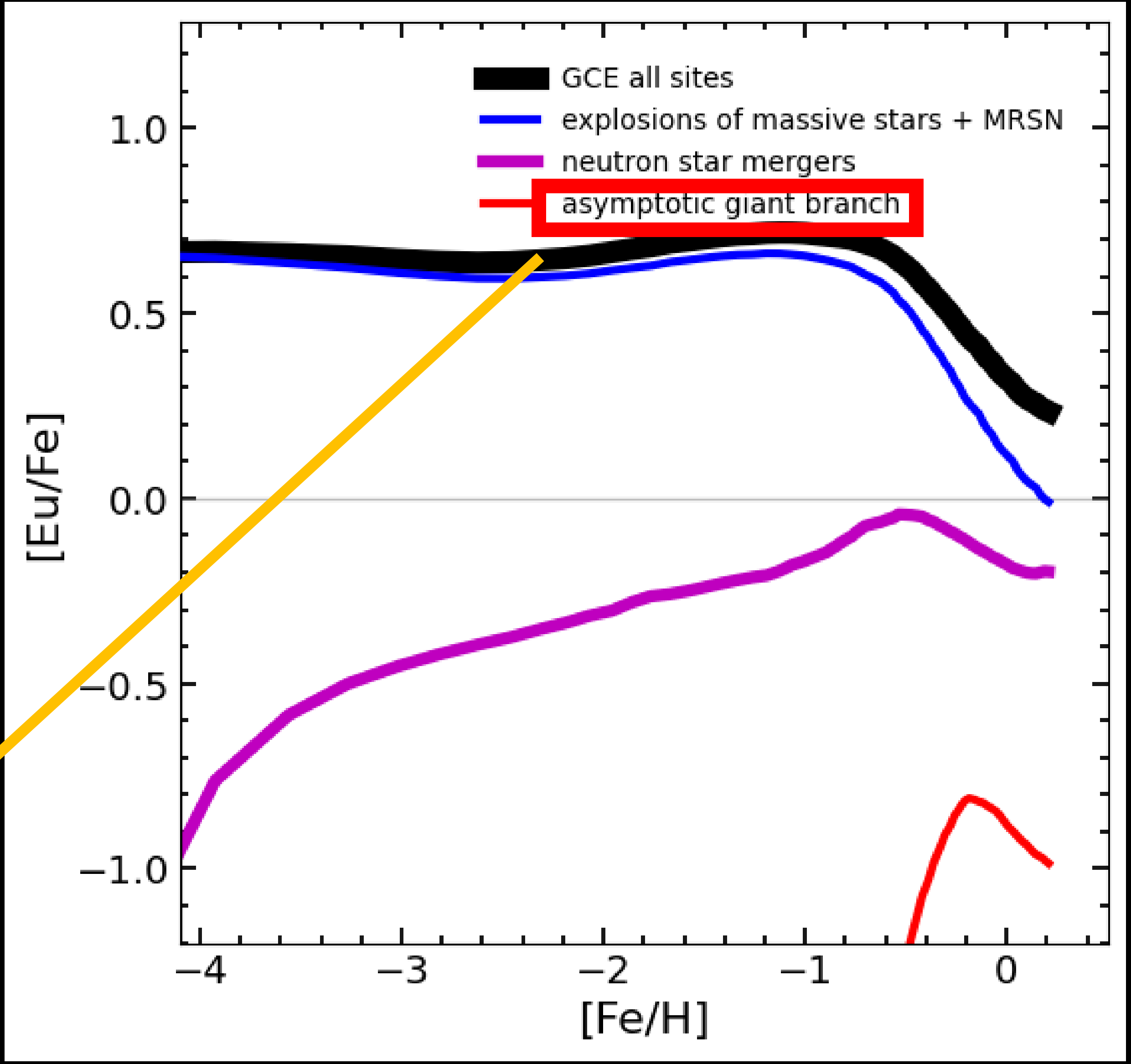

Low and intermediate mass stars, later in the galaxy

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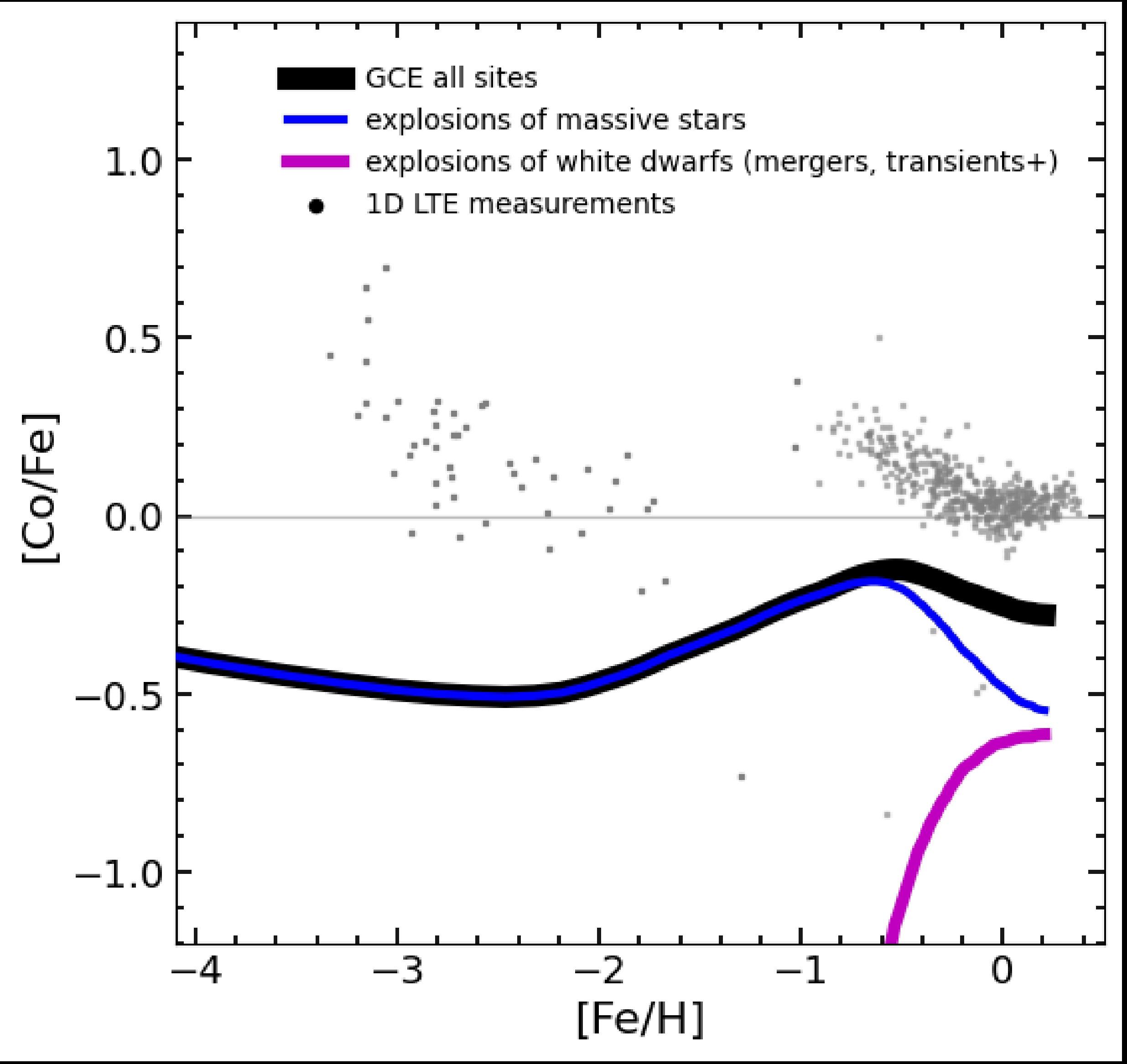
- Differences to observations:
    - GCE problems?
    - Inaccurate observations?



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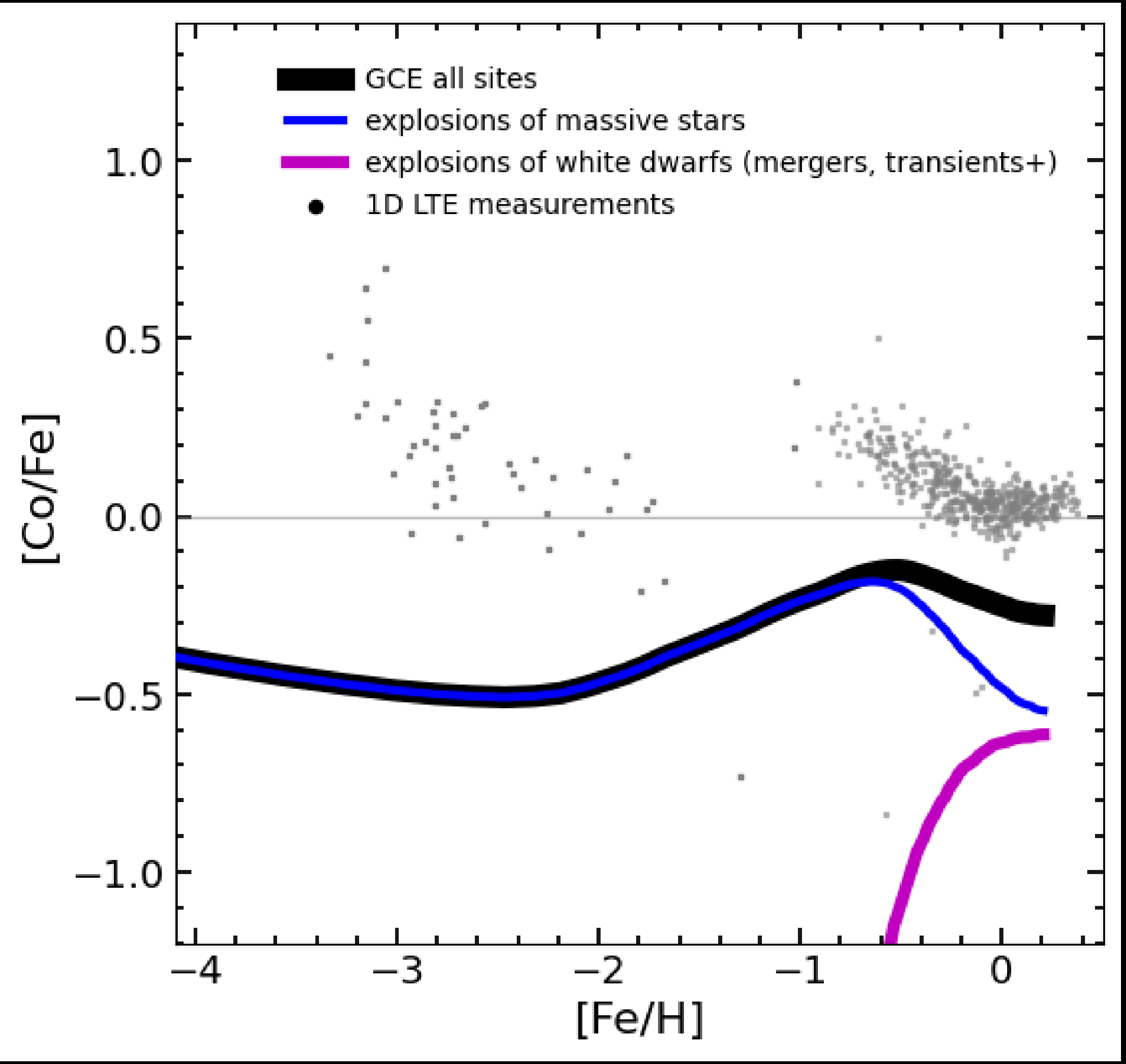

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Our approach: 3D RHD NLTE

- Get 3D NLTE corrections for 1D LTE literature abundances

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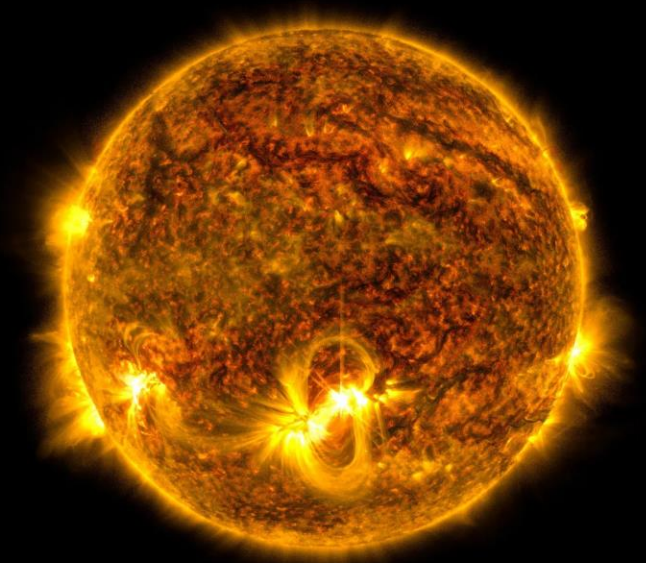
- Get 3D NLTE corrections for 1D LTE literature abundances
- Why 3D NLTE?
  - Stars are 3D objects (not 1D!)
  - Use 3D radiation-hydrodynamic model atmospheres
    - Validated and analysed in previous works, e.g. but not limited to Bergemann+19 & 21, Gallagher+20, Eitner+24, Storm+24, Guiglion+25



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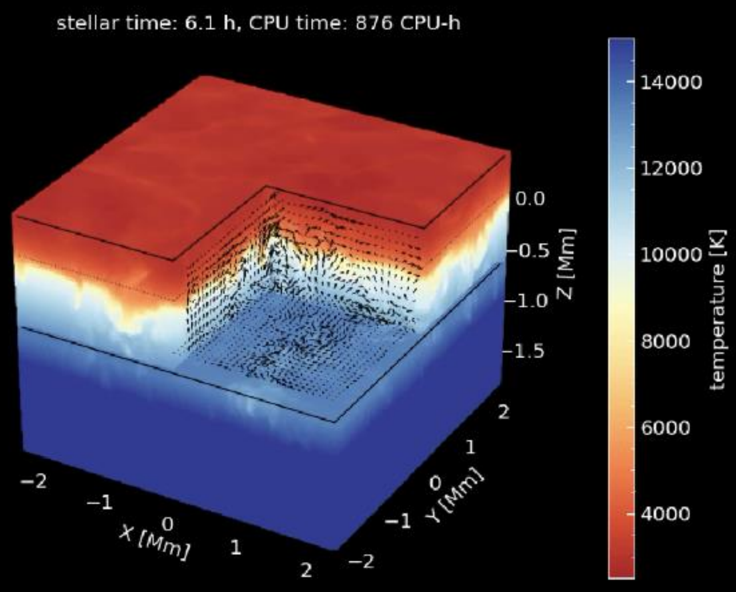

Eitner et al. 2024

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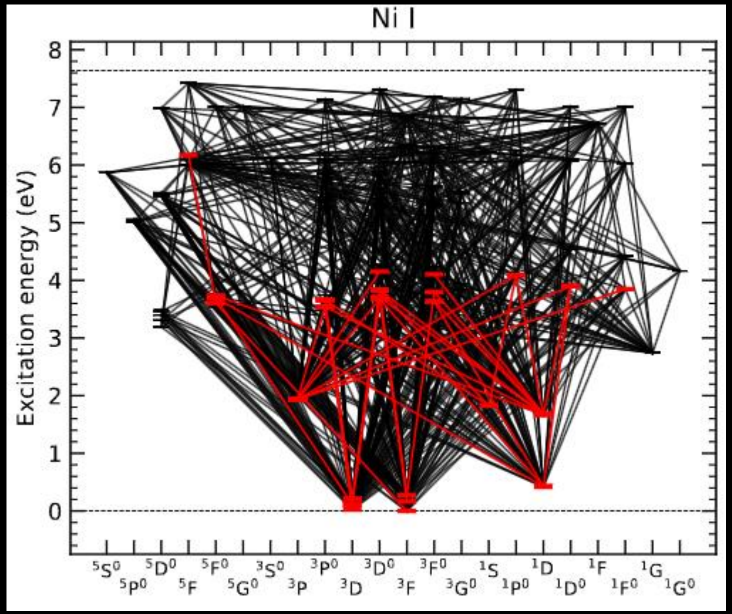
Our approach: 3D RHD NLTE

- Using developed NLTE atomic models
  - Grotrian diagram
  - See also Magg+22, Gerber+23
  - Tested on wide range of stellar parameters
  - See e.g.
    - Mn: Bergemann+19, Eitner+23, Ni: Bergemann+21, Magg+22, Y, Eu: Storm+23,24



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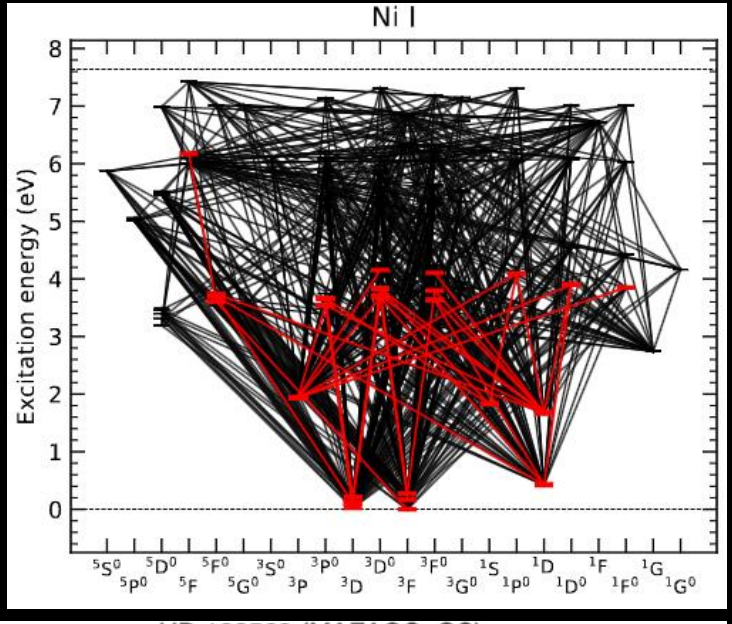
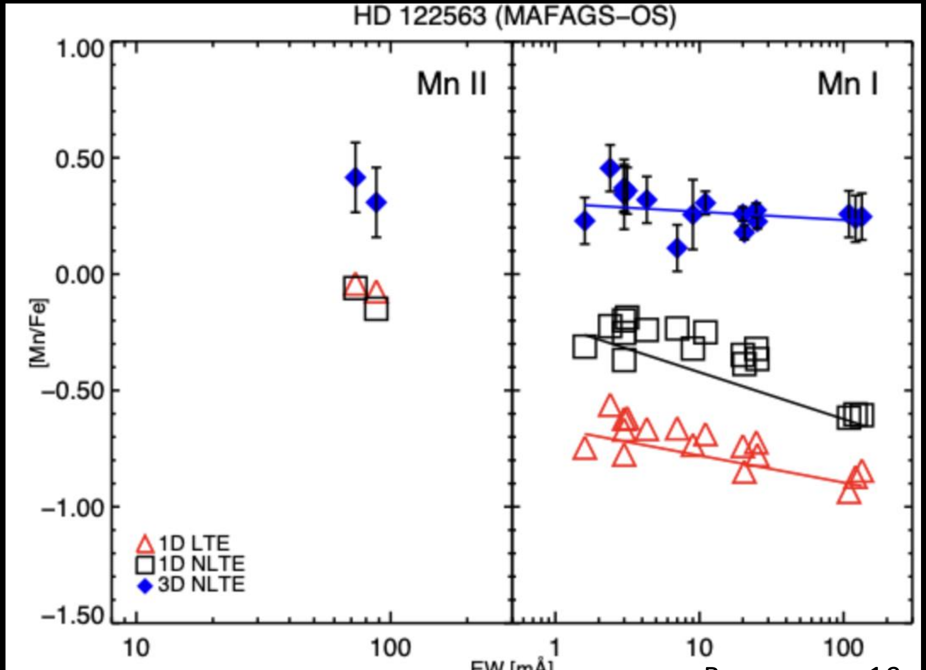


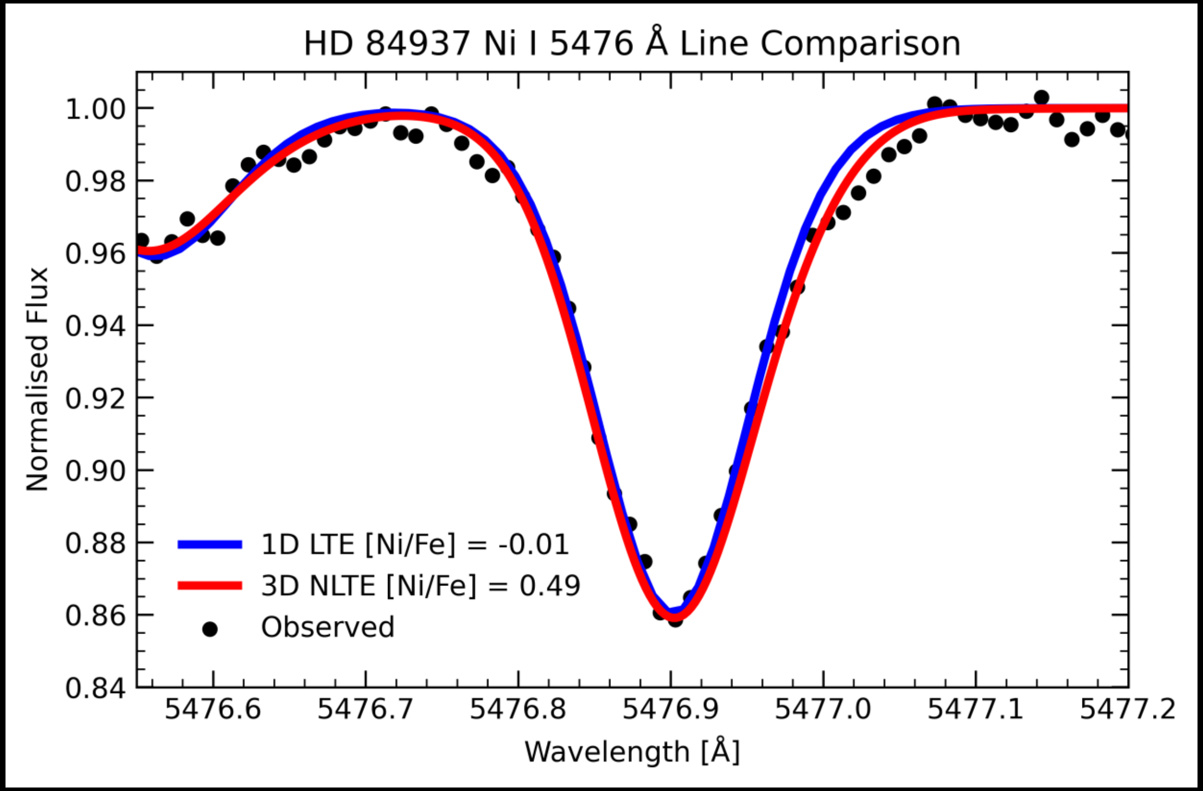


Bergemann+19

Results

3D NLTE effect on the line strength

- Example of one nickel line fit
  - HD 84937 (teff = 6350, log = 4.1, [Fe/H] = -2.1)
  - 3D NLTE line is much weaker
  - Thus derived 3D NLTE abundance higher than 1D LTE



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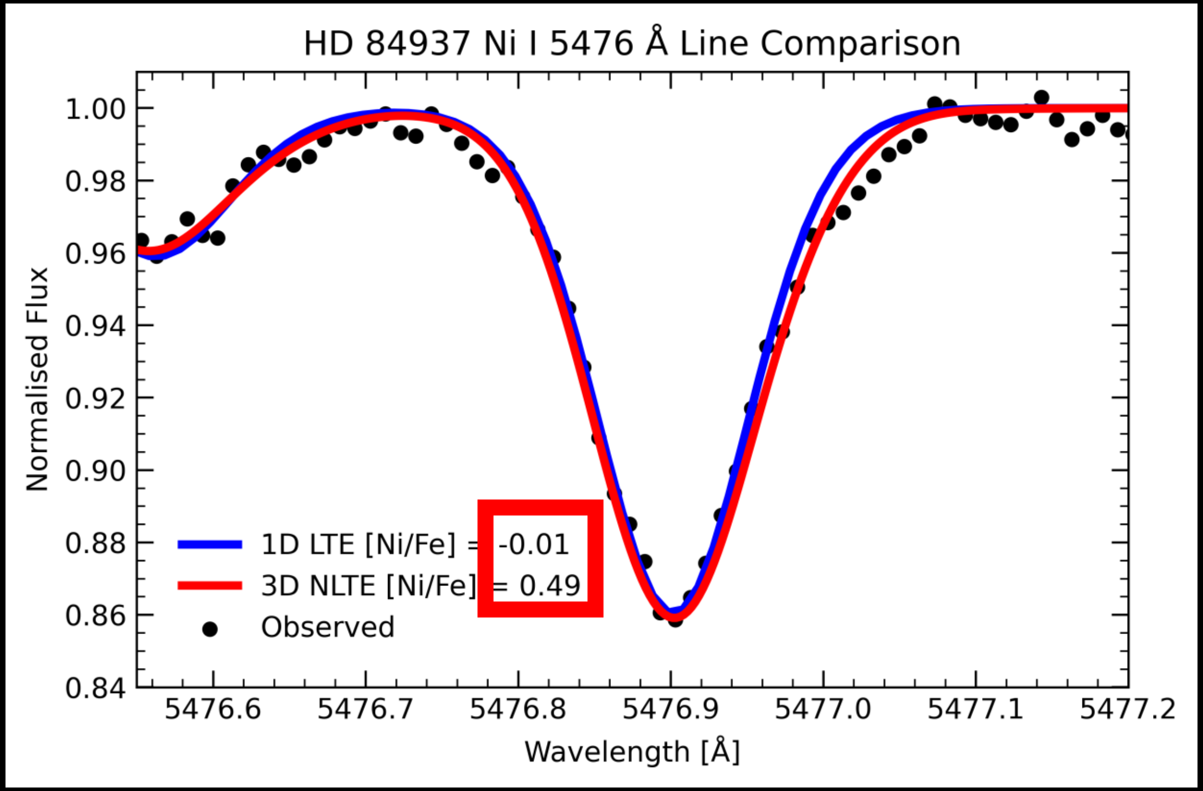
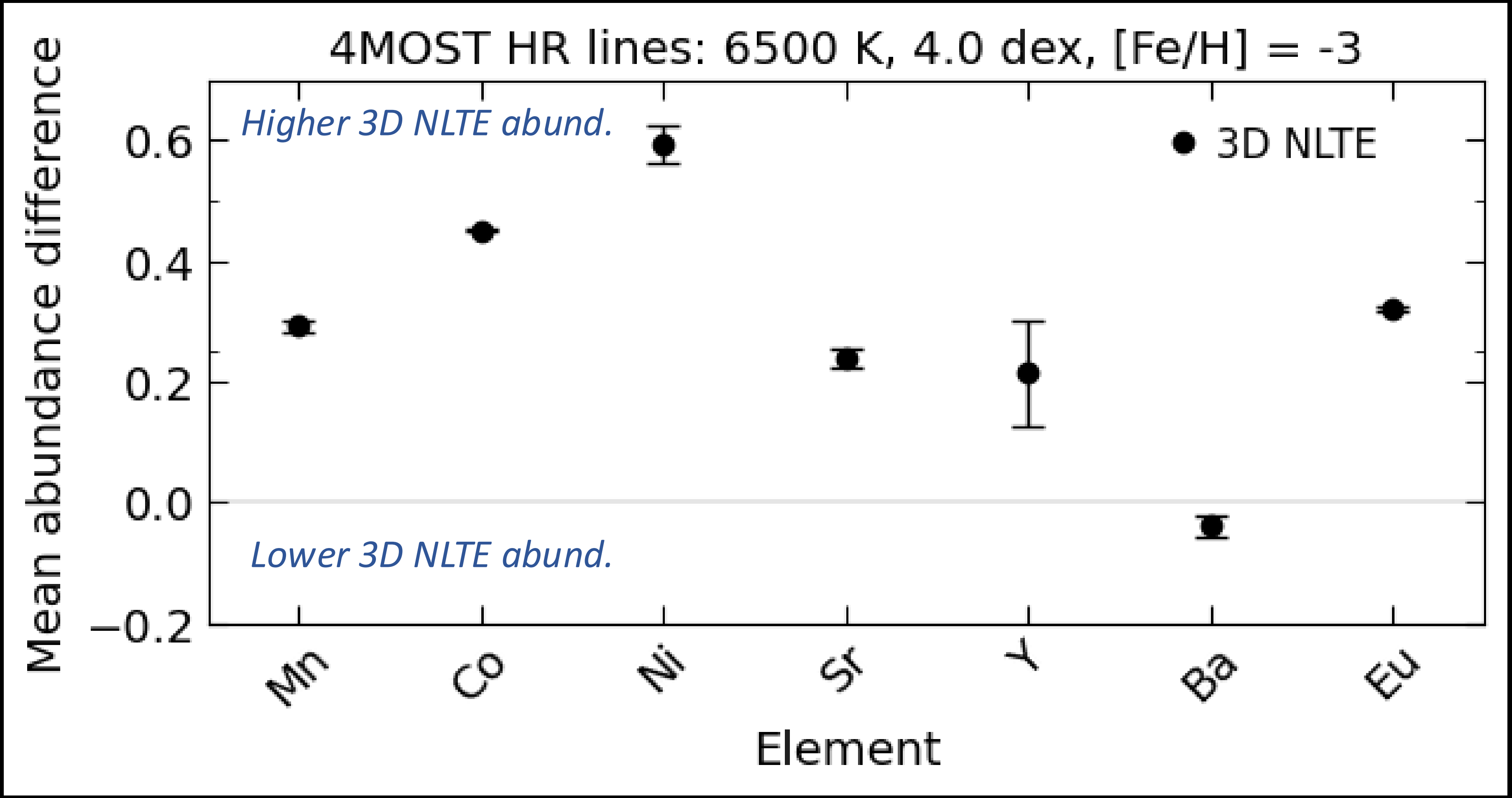


Difference between 3D NLTE and 1D LTE abundances



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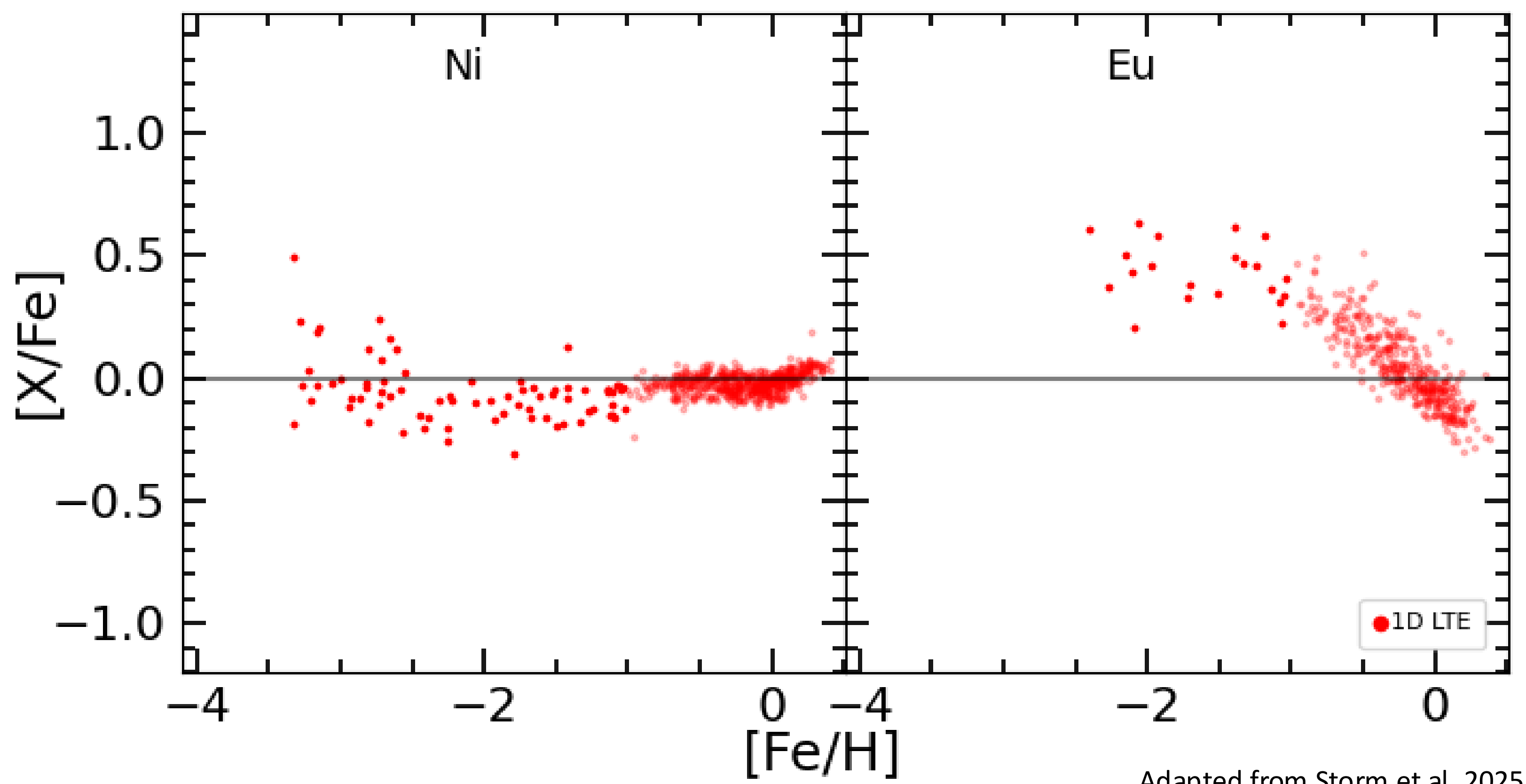
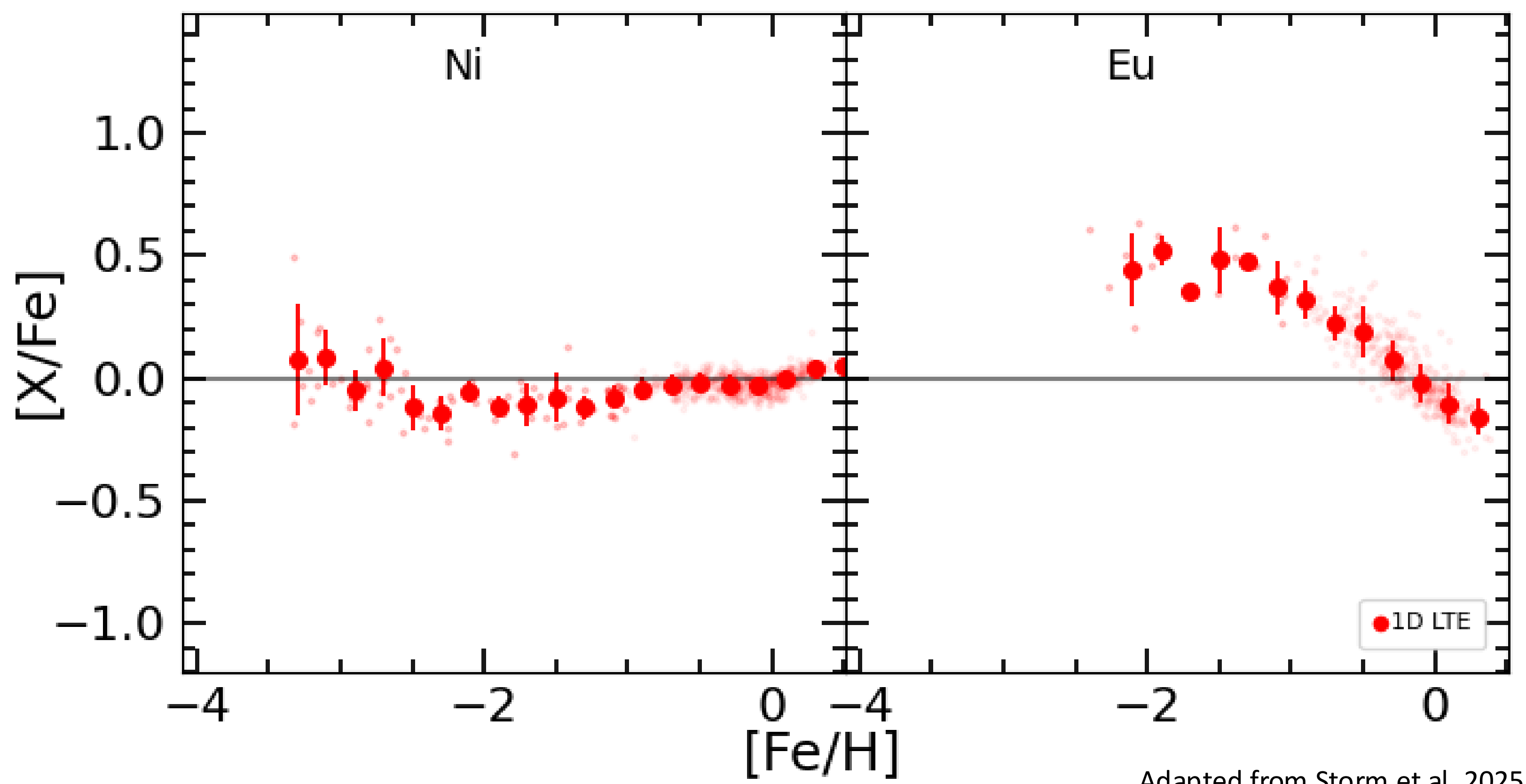
Effect on abundances

1D LTE literature abundances



Adapted from Storm et al. 2025

1D LTE Now binned



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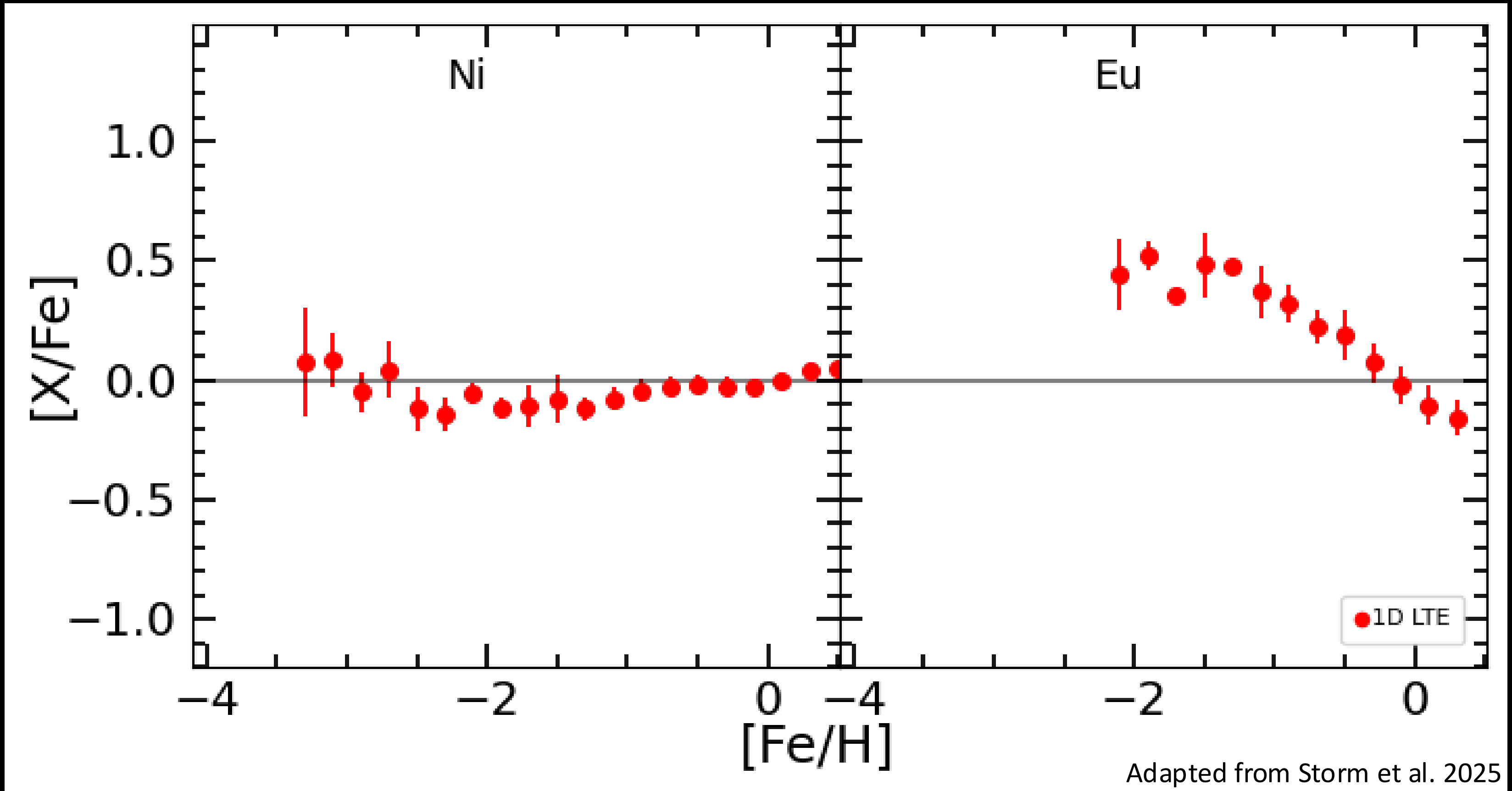
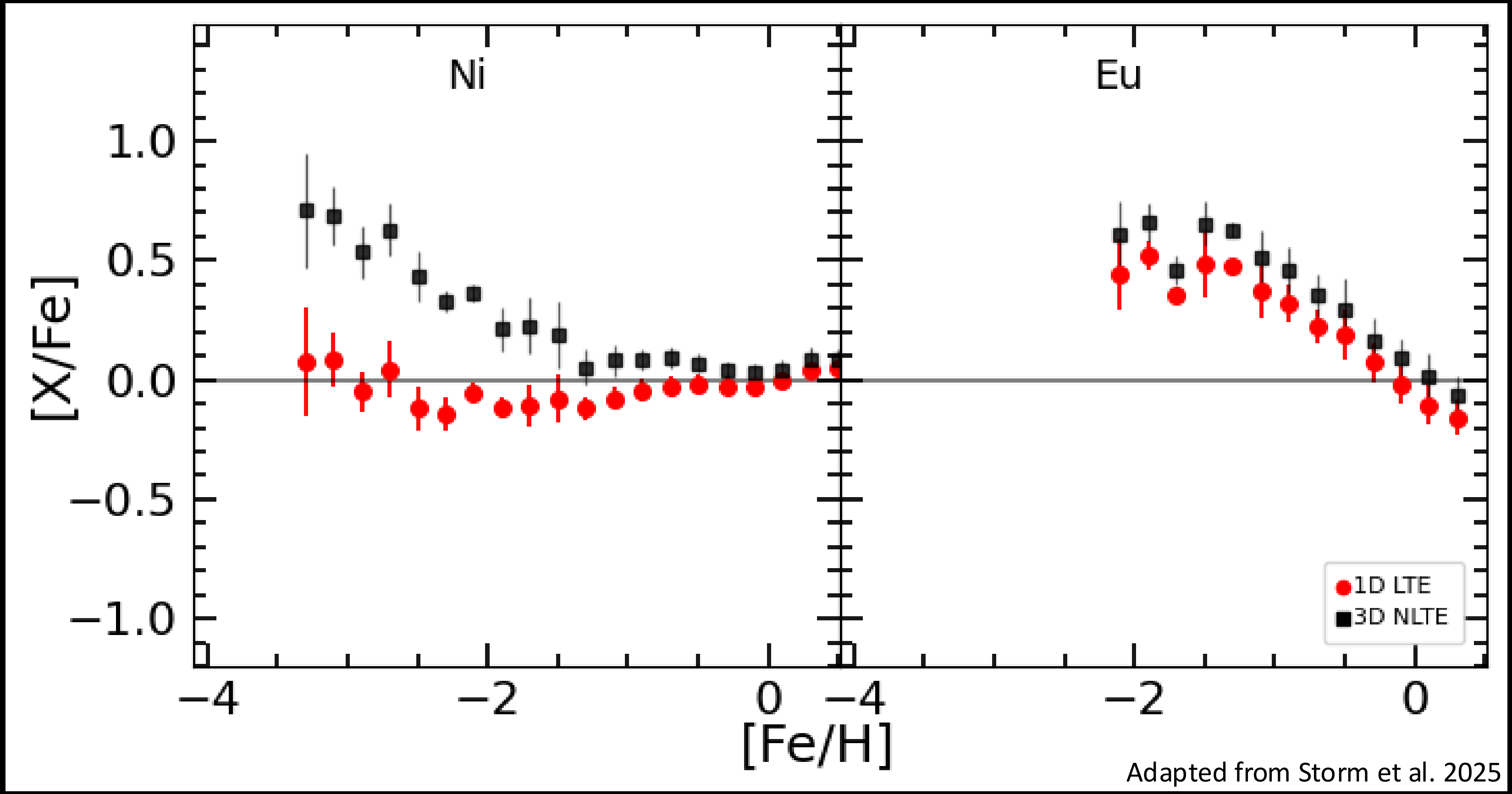


3D NLTE: higher abundance



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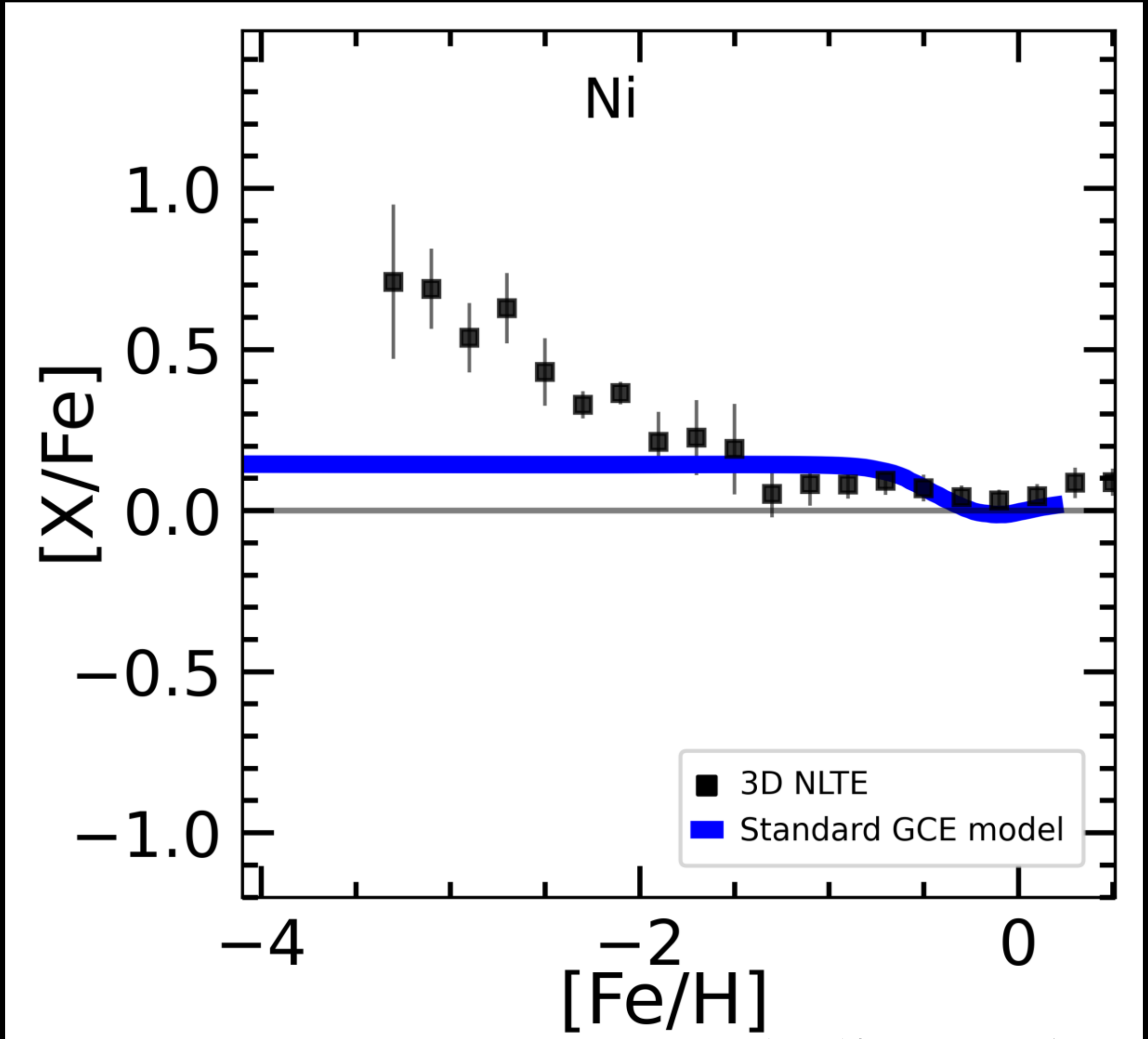
Comparison to GCE

Ni 3D NLTE

- Our “baseline” GCE model
  - OMEGA+ (Cote+ 17, 18)
  - CCSN yields
    - Limongi & Chieffi 2018
- GCE trend is flat
- 3D NLTE
  - Increasing trend with lower [Fe/H]
- GCE does not reproduce



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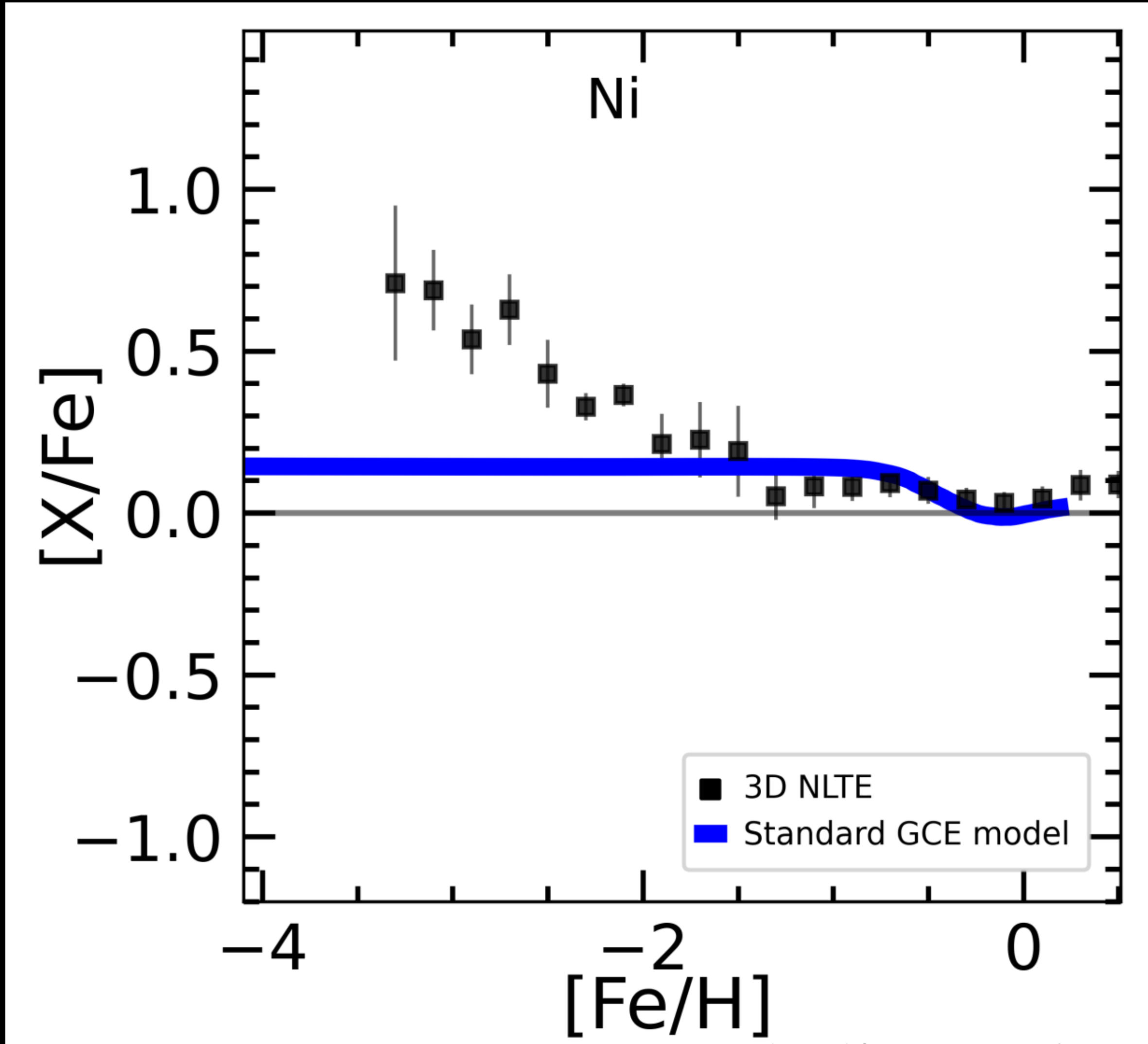
Ni 3D NLTE

- Different explanation needed
  - Need CCSN simulations in 3D at low [Fe/H]?
    - Not explored very extensively in literature so far
    - 3D effects important for iron-peak yields in CCSN, see e.g. Wanajo+11



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Ni 3D NLTE

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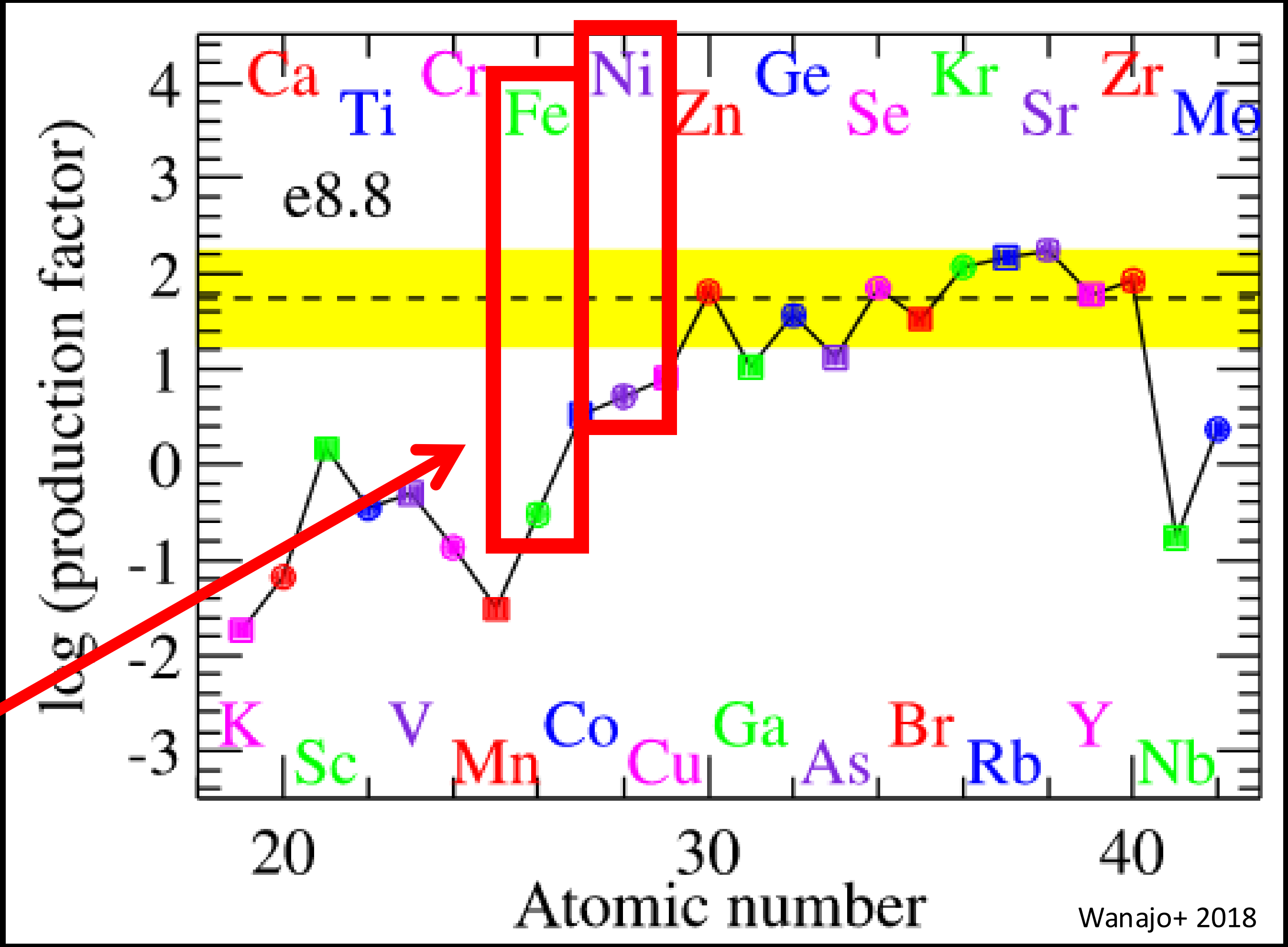
    - Not explored very extensively in literature so far
    - 3D effects important for iron-peak yields in CCSN, see e.g. Wanajo+11
  - Or another production site?
    - ECSN?
      - Models predict higher Ni/Fe yields (Nomoto+87; Wanajo+18; Zha+22)
      - Need more bottom-heavy IMF in the early Galaxy?



Ni 3D NLTE

- See also recent JWST observations of Crab Nebula (ECSN or low-mass CCSN remnant?)
  - [Ni/Fe] 3-5 larger than solar ones (Temim+24)

Temim+ 2024

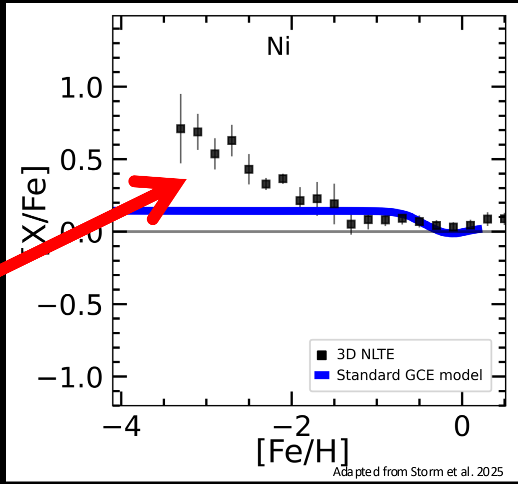
Table 3
Derived Nickel-to-iron Ratios

		Derived					
		Position 1 (blue)			Position 1 (red)		
Line Ratio	$C_{\text{ion.bal.}}$	Ion	Abund.	×Solar	Ion	Abund.	×Solar
[Ni II]/[Fe II]	1.61	0.152	0.245	4.6	0.162	0.261	4.9
[Ni III]/[Fe III]	1.13	0.160	0.18	3.4	0.138	0.156	2.9

Conclusions

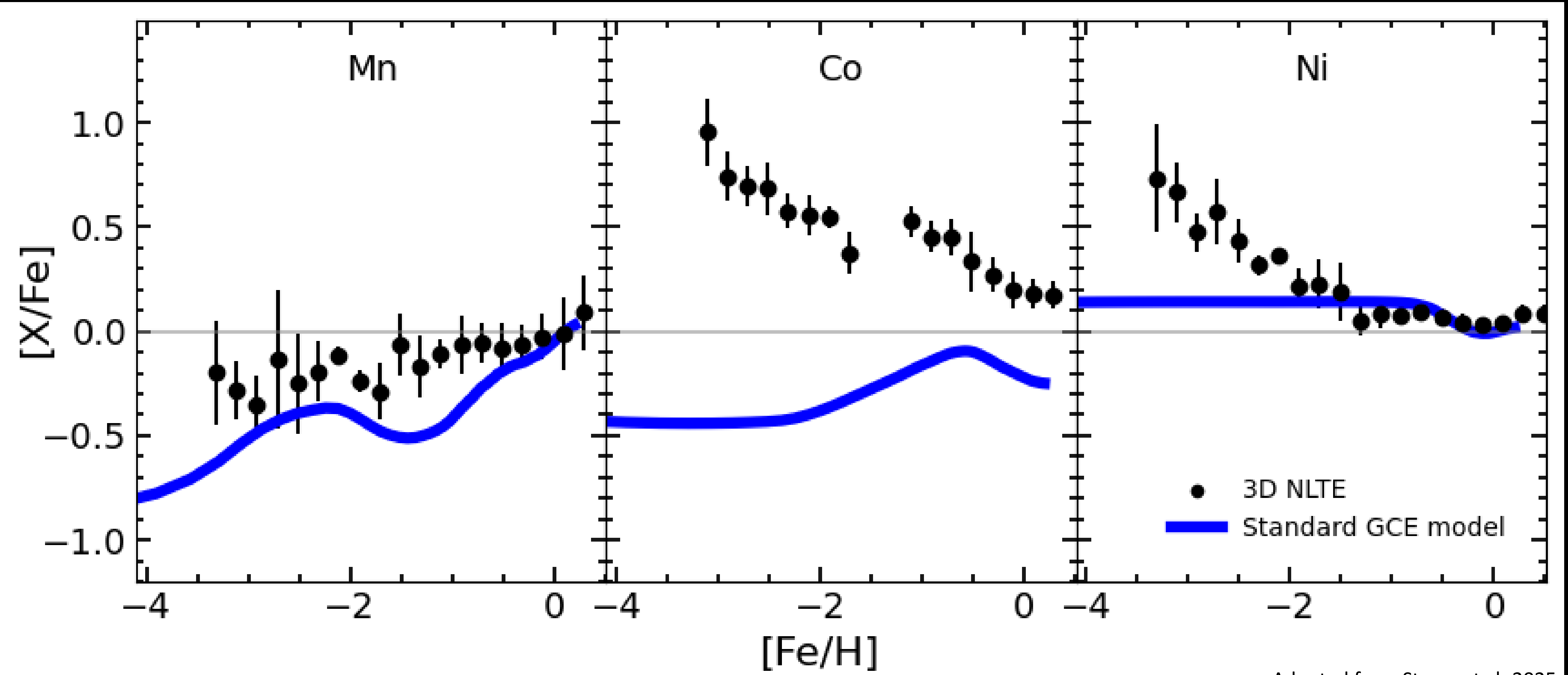
Conclusions

- 3D NLTE is necessary to provide robust chemical abundances, as the models are parameter-free
  - No mixing-length, no assumption of Saha-Boltzmann equilibrium, no Vmic
  - See e.g. Bergemann+19, Lind & Amarsi+24
- Iron-peak elements
  - GCE models of the disc (OMEGA+) based on state-of-the-art yields (Limongi & Chieffi 2018) do not explain the chemical evolution of Fe-group elements
  - CCSN-dominated regime is under-produced in the GCE tracks
  - ECSN have [Ni/Fe] >> 0, which could help? (Wanajo+18)
- More elements are also done: Mn, Co, Ni, Sr, Y, Ba, Eu (see Storm+2025)



Bonus slides

Iron-peak elements 3D NLTE



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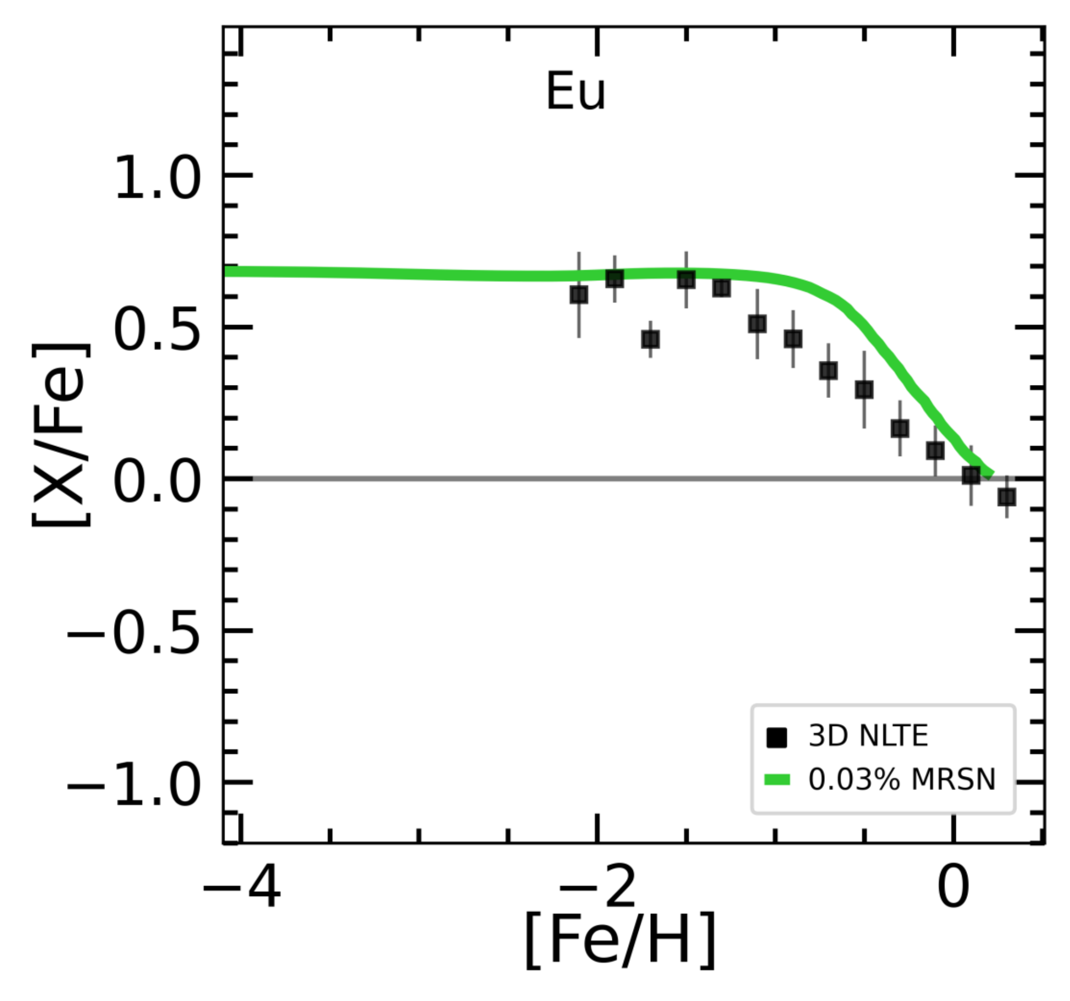
Eu
1.0
0.5
0.0
−0.5
−1.0
[X/Fe]
−4
−2
0
[Fe/H]
3D NLTE
0.03% MRSN