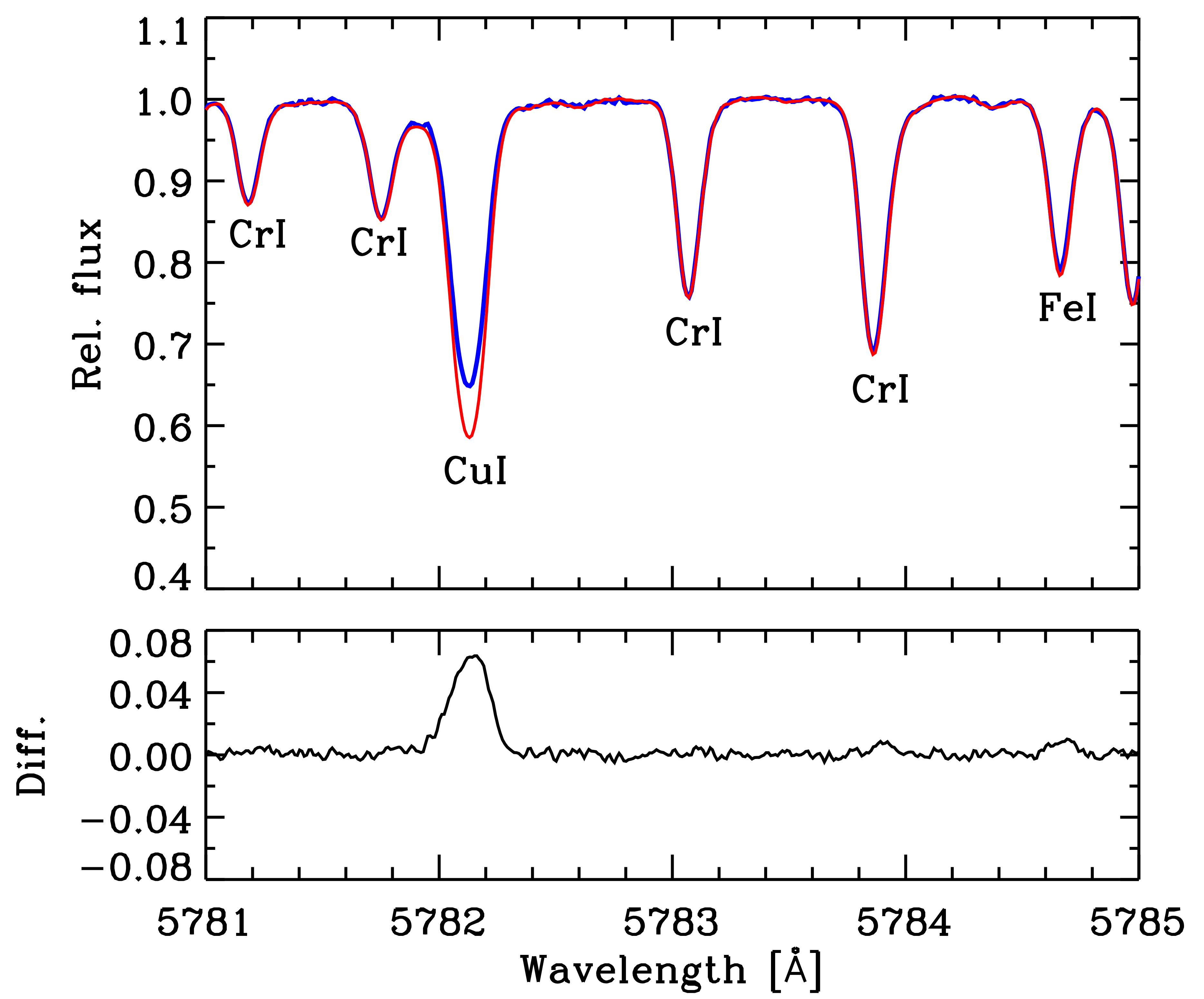
Atomic data needs for non-LTE modelling of stellar spectra

Anish Amarsi (Uppsala University)

CompAS meeting, Lund, 12 June 2025

Measuring elemental abundances

- Infer parameters/compositions by comparing observed stellar spectrum to theoretical model stellar spectra

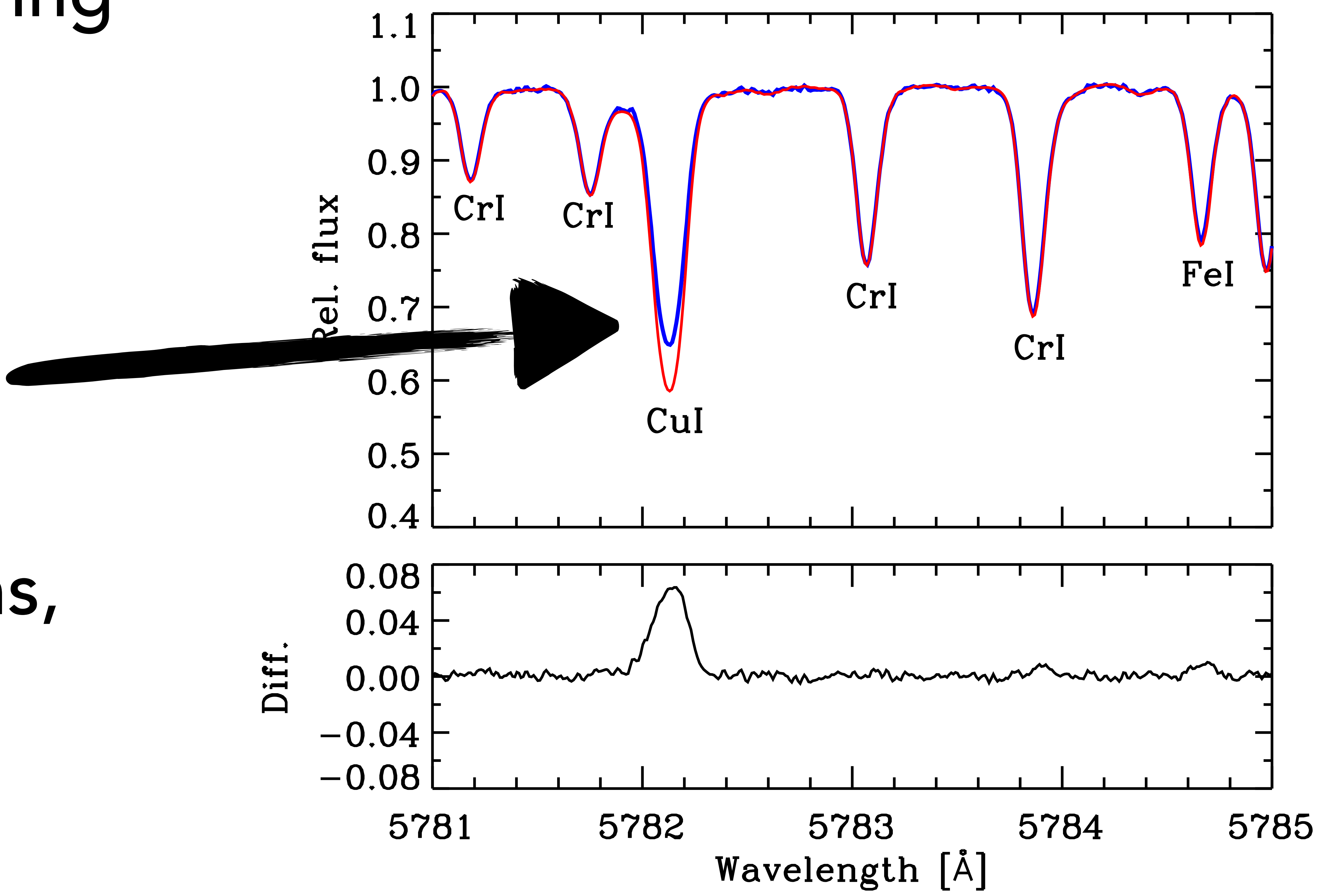


[Nissen & Gustafsson 2018]

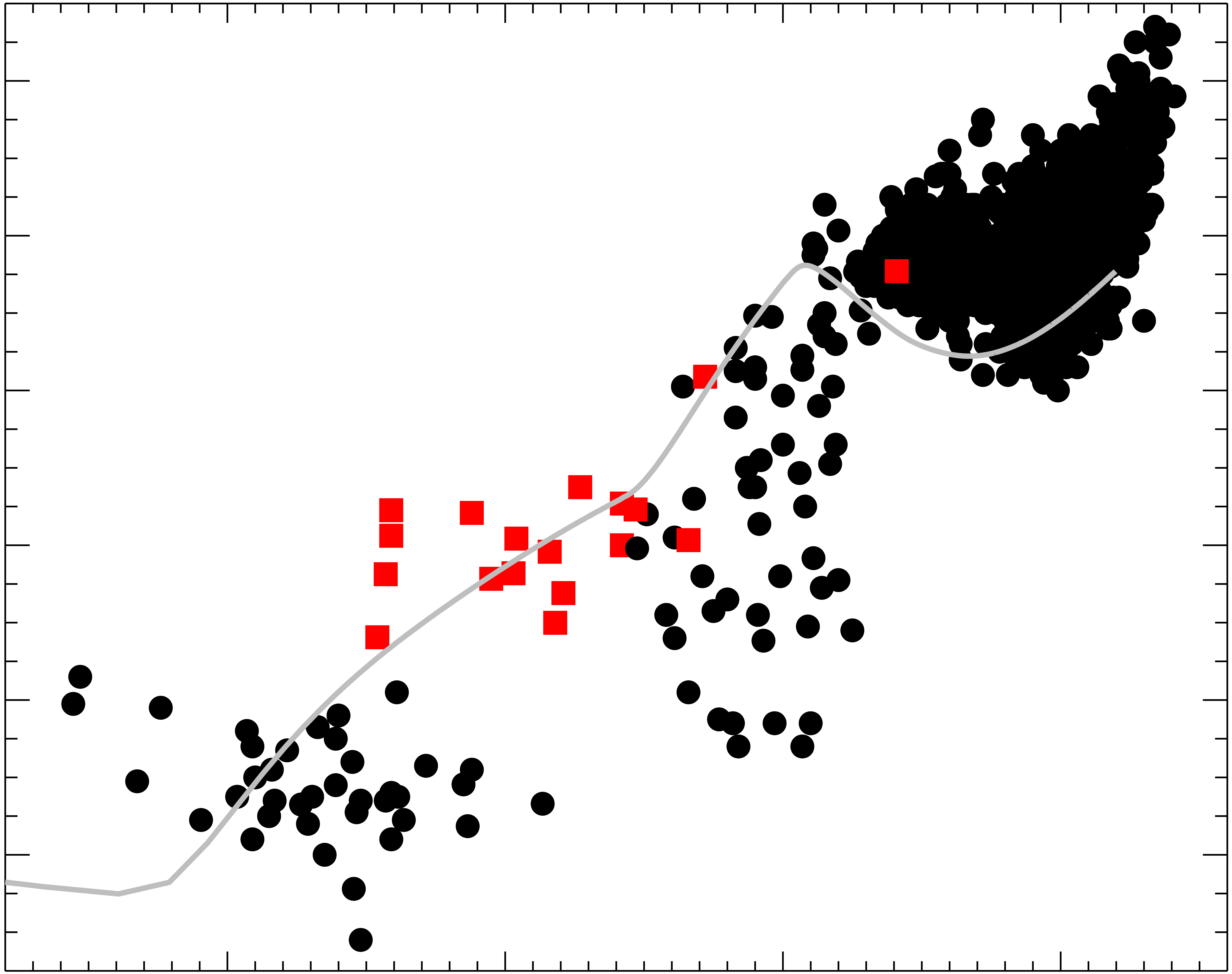
Measuring elemental abundances

- Infer parameters/compositions by comparing observed stellar spectrum to theoretical model stellar spectra
- Here: lower the copper abundance in the model to agree with observations
- Interpret abundances to learn about atoms, planets, stars, galaxies…

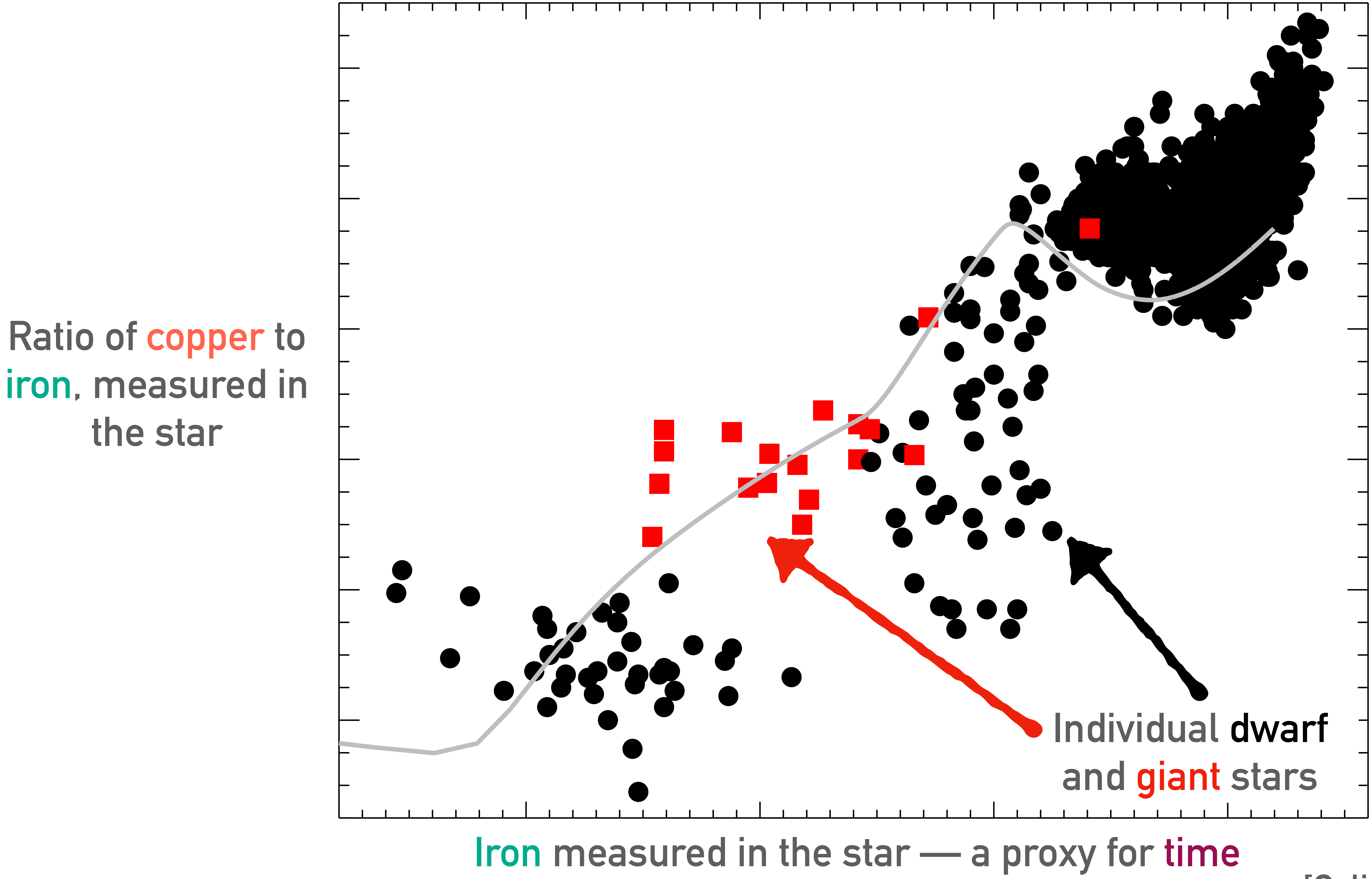
Neutral copper line



[Nissen & Gustafsson 2018]



[Caliskan et al. 2025]

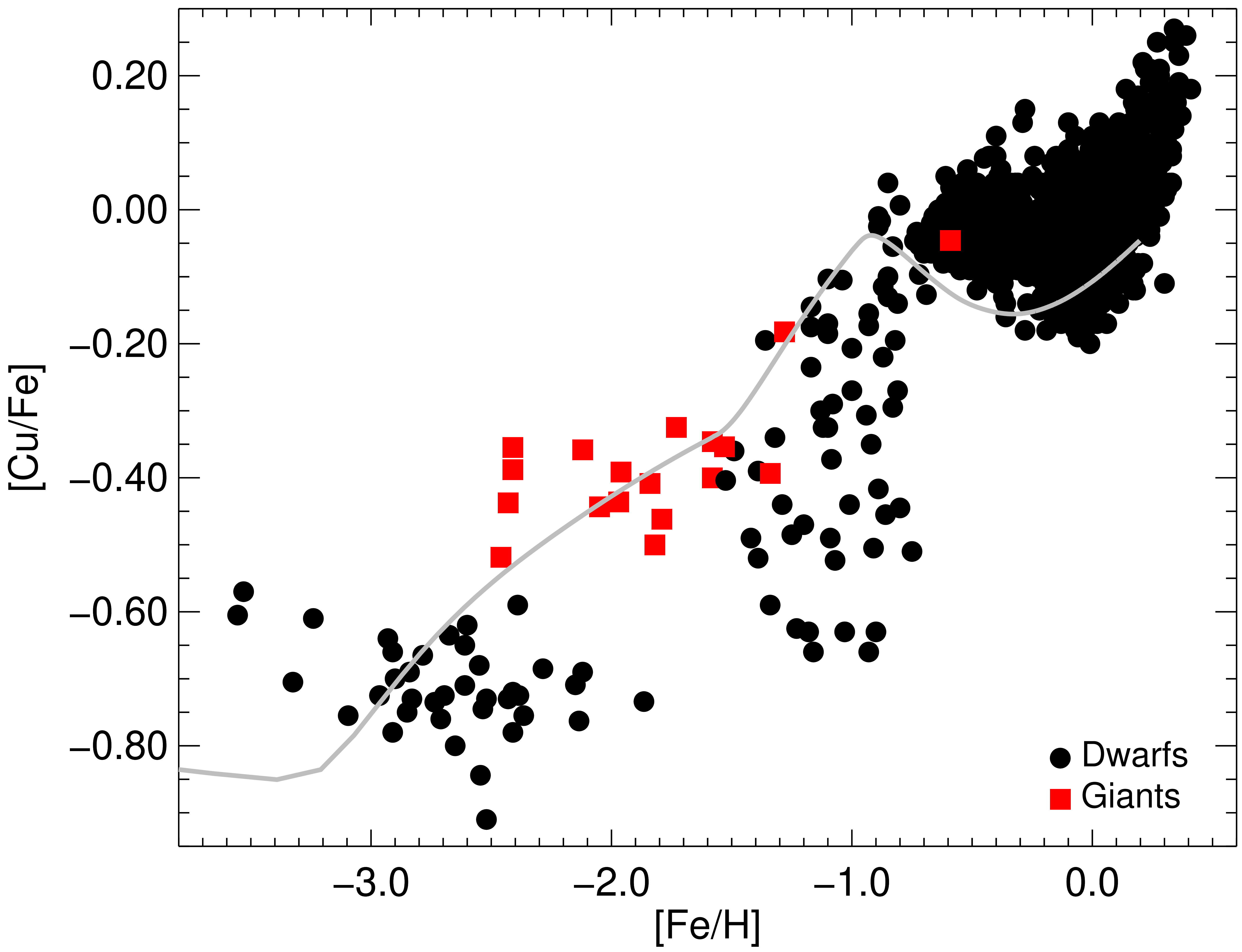


[Caliskan et al. 2025]


Model of the Galaxy
(Kobayashi et al. 2020)
Ratio of copper to iron, measured in the star
Individual dwarf and giant stars
Iron measured in the star — a proxy for time
[Caliskan et al. 2025]

How galaxies make pennies

- Extremely steep gradient
- Copper production in the Galaxy ramps up with time
- Constraints on stellar structure, evolution, nucleosynthesis; and Galactic modelling



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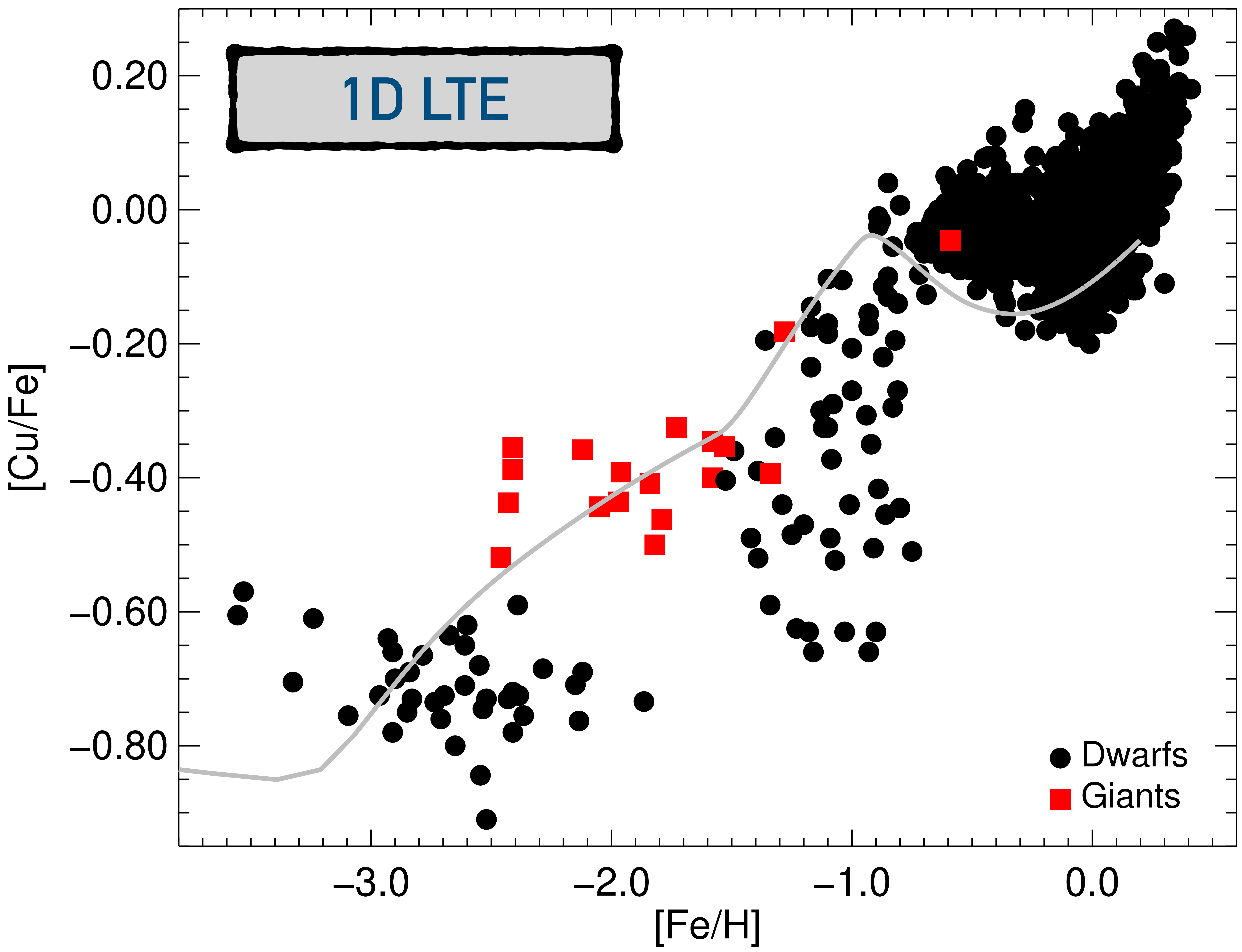

[Caliskan et al. 2025]


Spectrum
Radiative transfer
Atmosphere models
Knowledge
e.g. origins of elements
Stellar parameters
e.g. composition
H
He
O
Fe
F
Sc
Ba
Pb
Li
U
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4
6
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10
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80
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Macrophysics
(e.g. 3D)
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Atom producing
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Perturbations from
fast electrons
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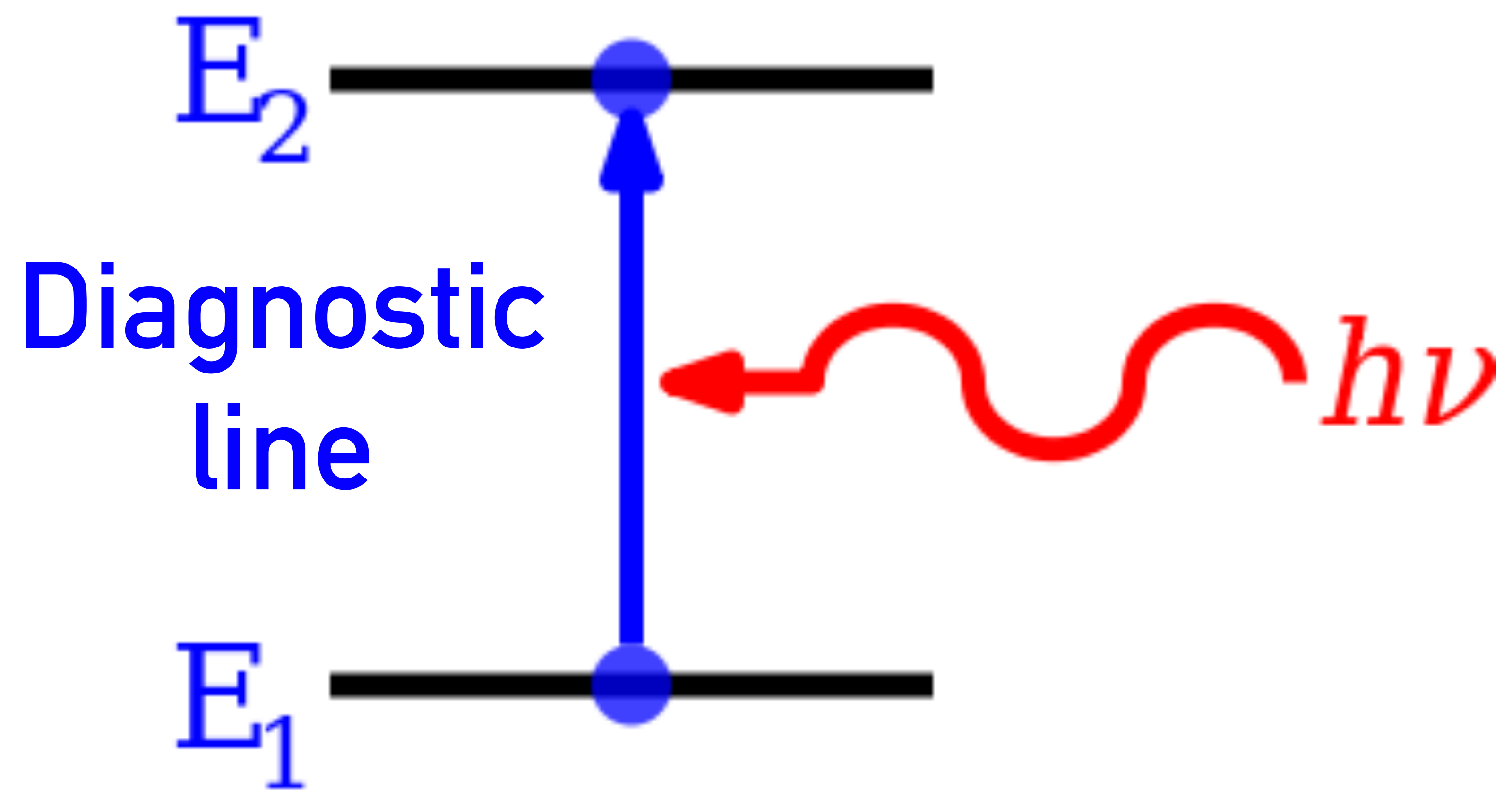
The LTE assumption

- Absorption line strengths depend on **number of absorbers and emitters** in the correct energy states



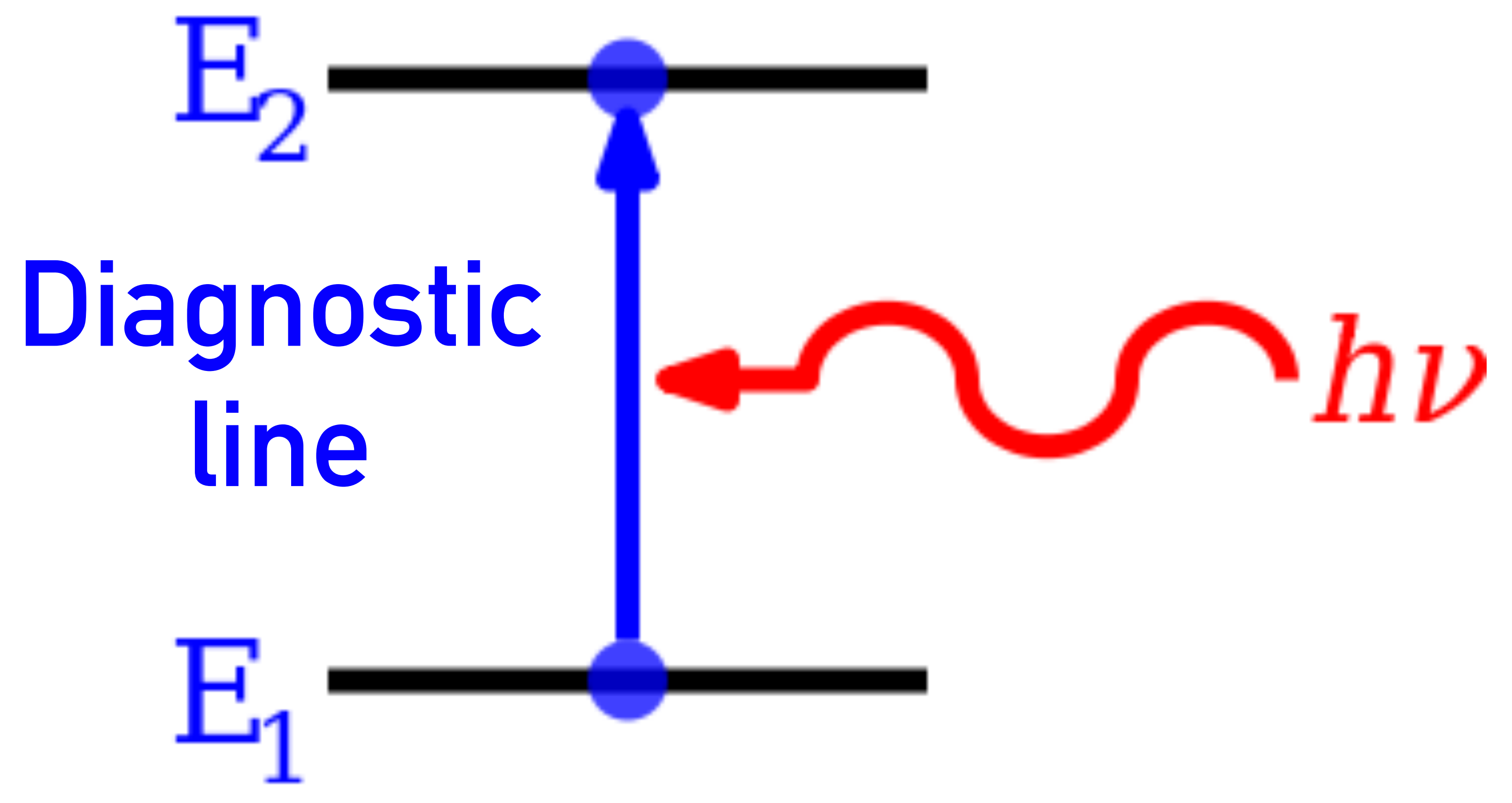
The LTE assumption

$$\frac{n_2}{n_1} = \frac{g_2}{g_1} \exp\left(-\frac{\Delta E_{1\to 2}}{k_\mathrm{B} T}\right)$$

- Absorption line strengths depend on **number of absorbers and emitters** in the correct energy states

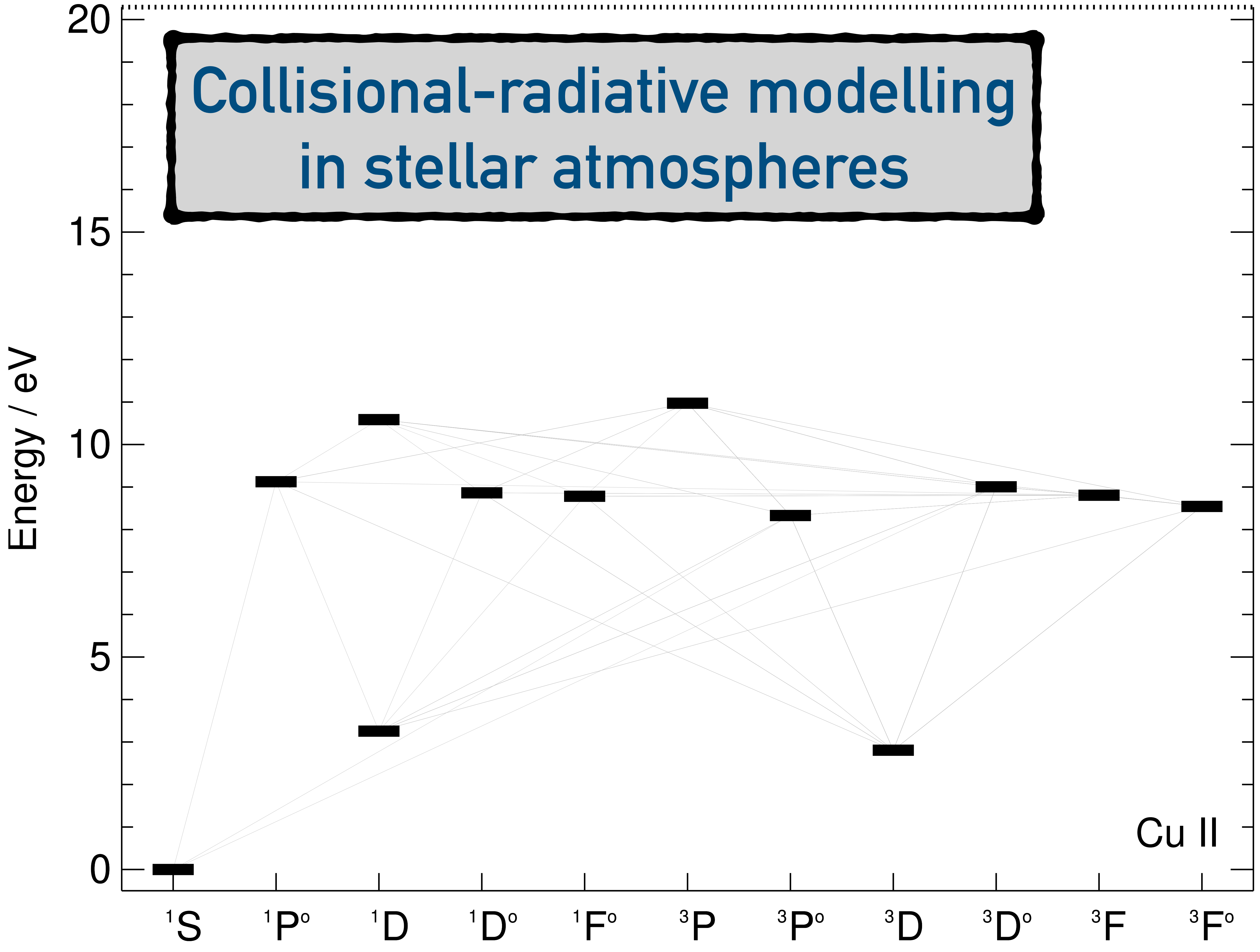
- Local thermodynamic equilibrium (LTE): trivially known via **Boltzmann and Saha distributions**

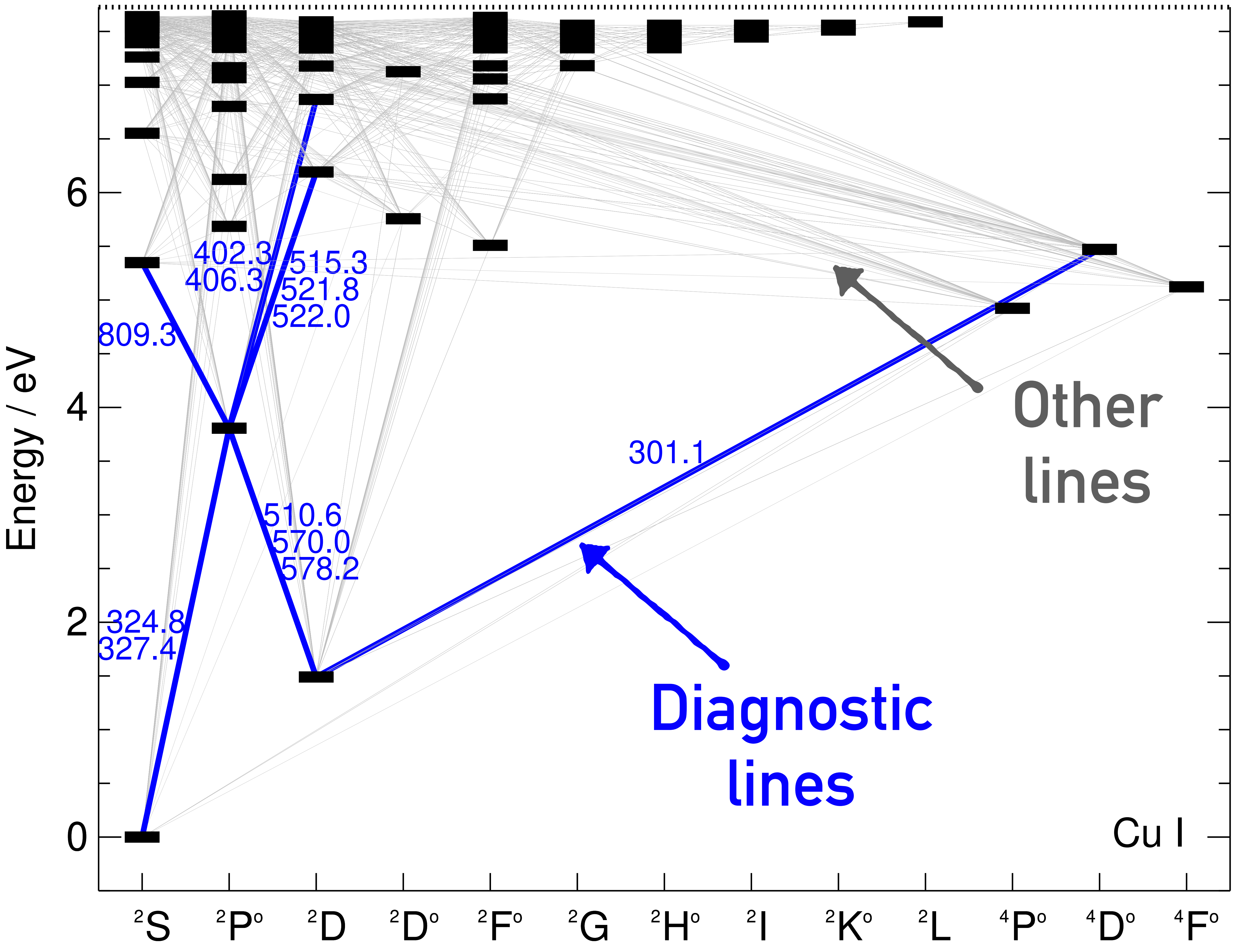
- Underlying assumption: **efficient collisional coupling**



$$n_e \frac{N_\mathrm{II}}{N_\mathrm{I}} = \frac{2}{\Lambda^3} \frac{Z_\mathrm{II}}{Z_\mathrm{I}} \exp\left(-\frac{\Delta E_{\mathrm{I}\to\mathrm{II}}}{k_\mathrm{B} T}\right)$$

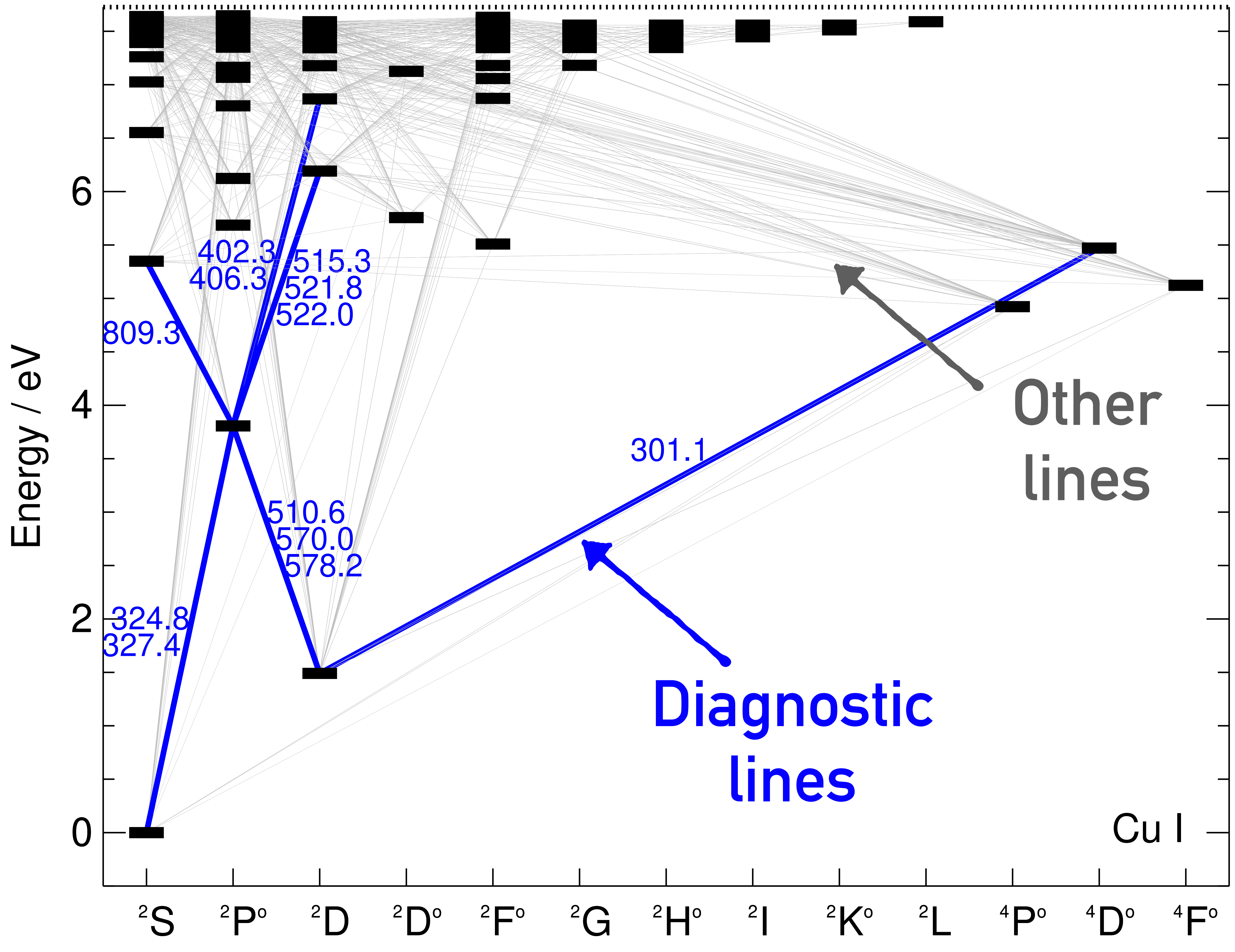
Relaxing the LTE assumption





Relaxing the LTE assumption

- **Statistical equilibrium:**
  $n_i \Sigma_j [R_{ij} + C_{ij}] = \Sigma_j n_j [R_{ji} + C_{ji}]$
- ***C*** are collisional rates, depend on **local Maxwellian-averaged** cross-sections
- ***R*** are radiative rates: e.g.
  $R_{lu} = \int_0^\infty B_{lu} J_\nu \varphi\left(\nu - \nu_0\right) \mathrm{d}\nu$, with radiation field J_ν (determined via **radiative transfer equation**) coupling different parts of atmosphere



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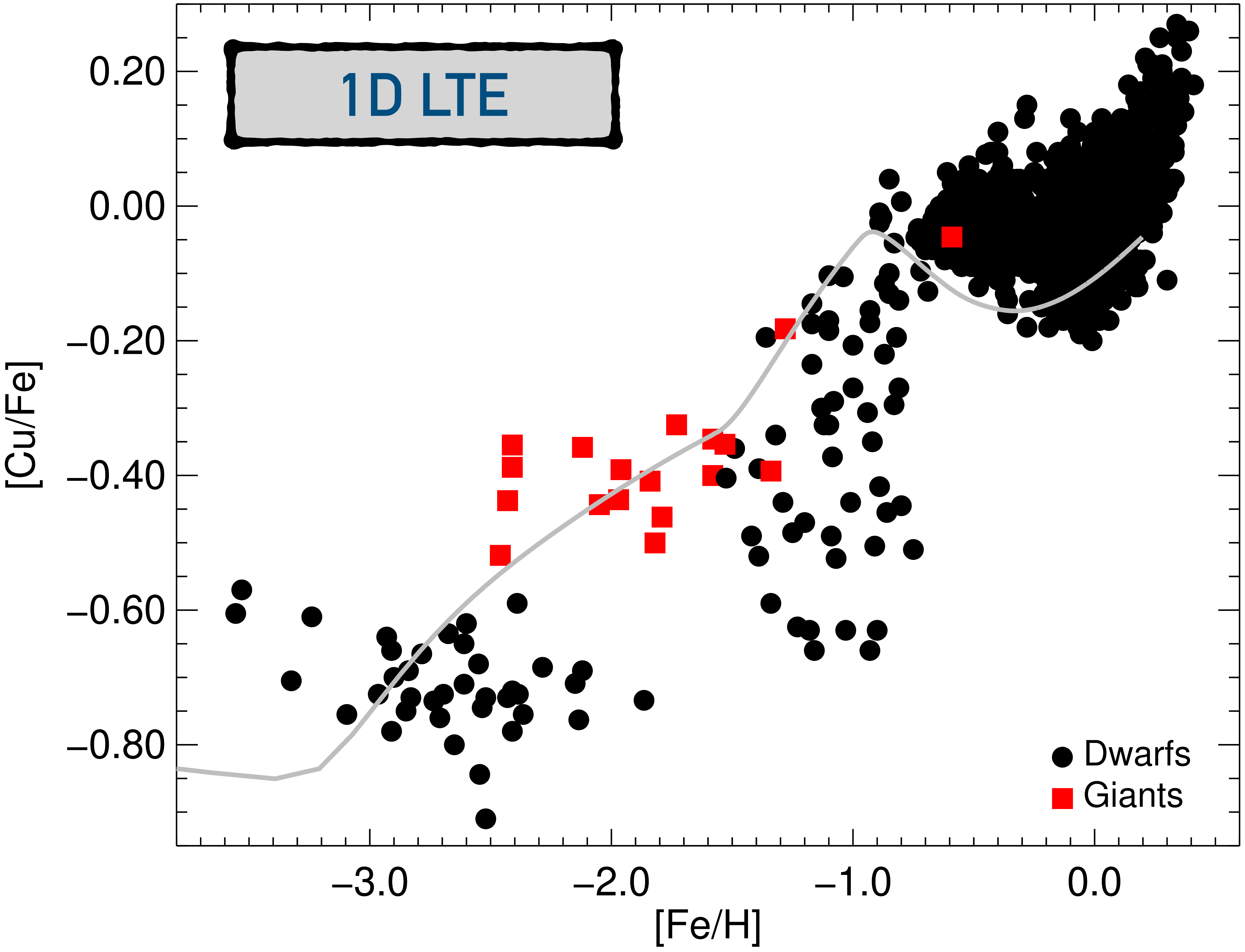

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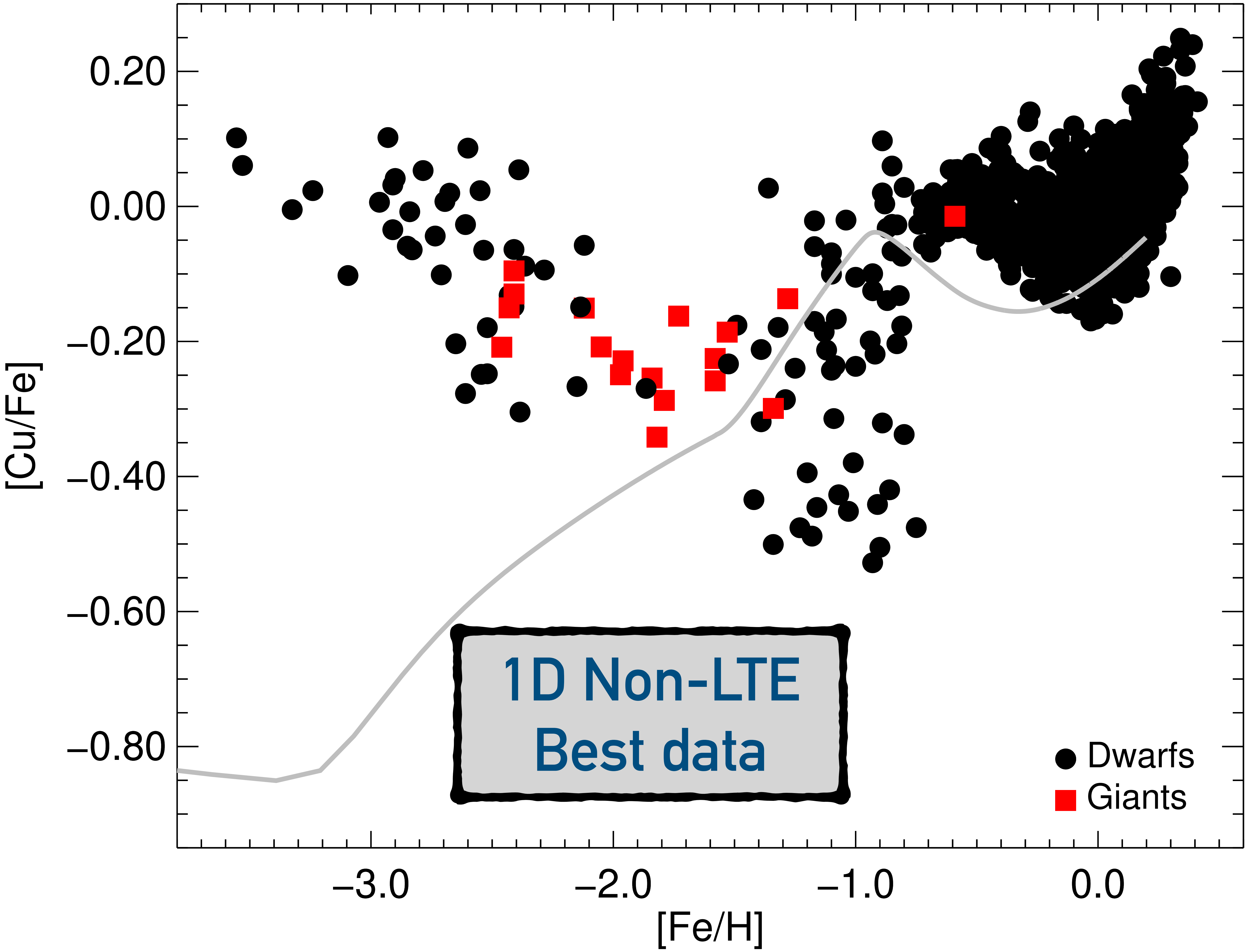

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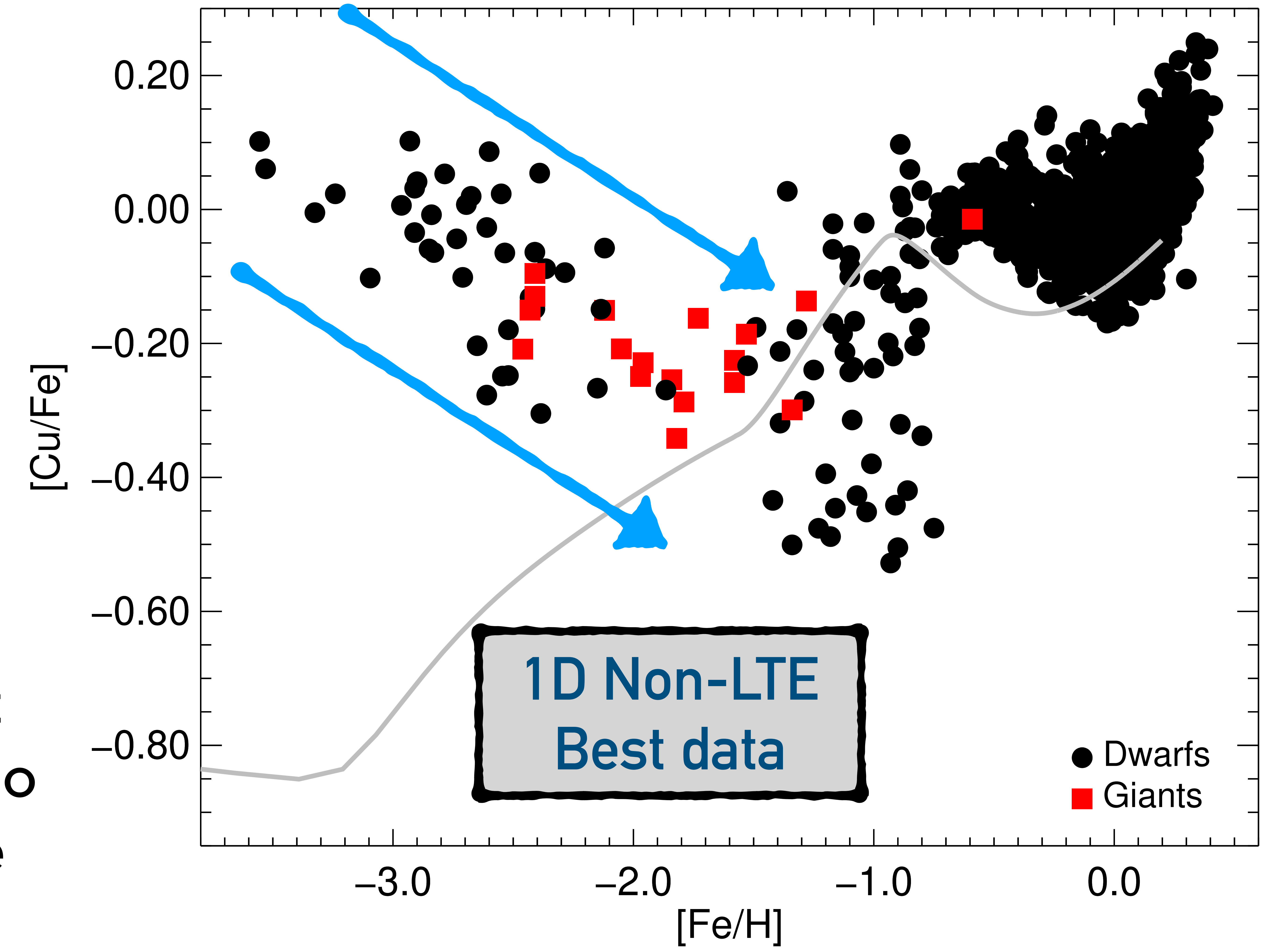
How galaxies make pennies

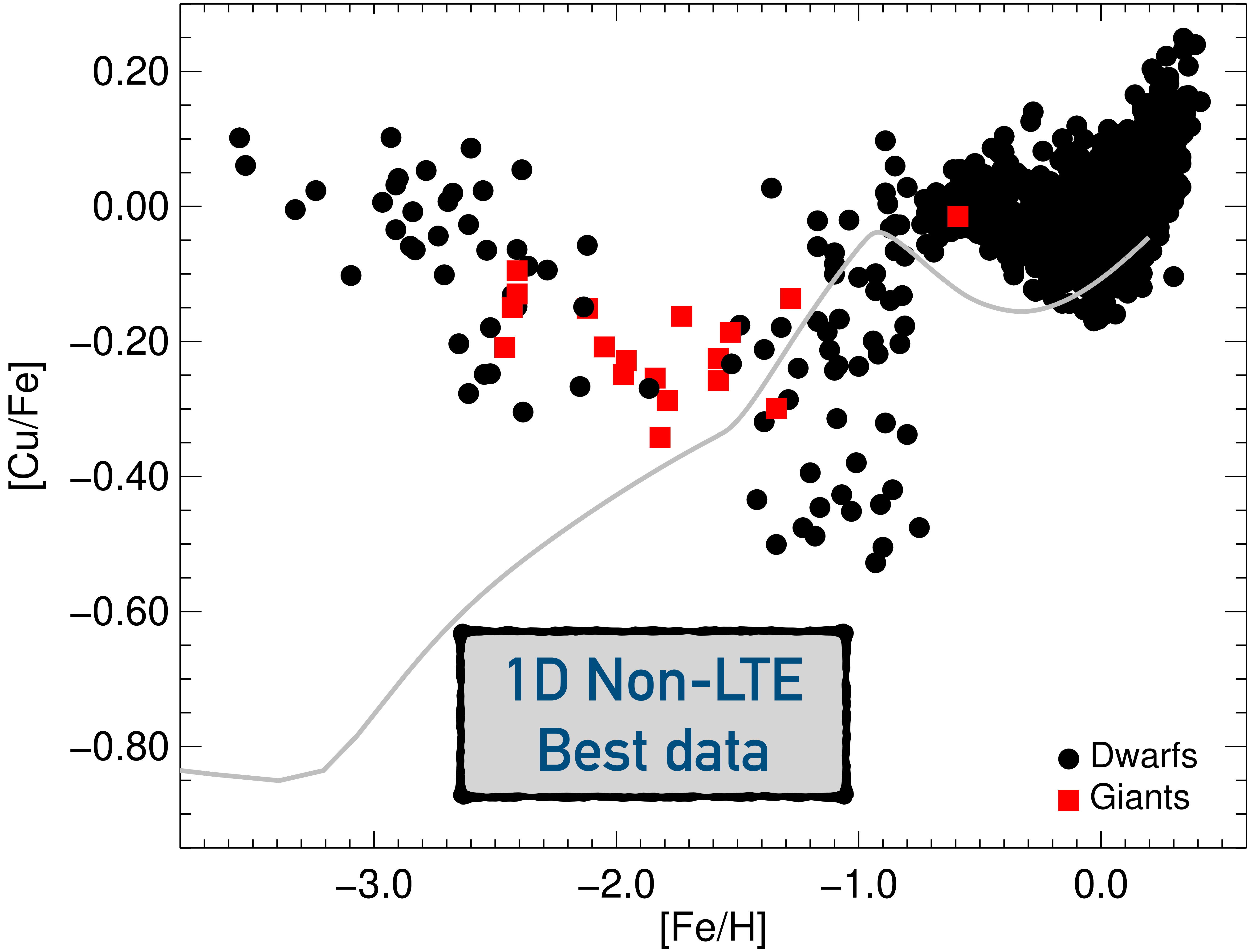
- Non-LTE: opposite trend in copper to iron
- Our interpretation: a new signature (and test) of the **hierarchical formation of the Milky Way**
- Consistency checks: agreement between **dwarfs** and **giants**; also reduced line-to-line scatter (see the paper)



[Caliskan et al. 2025]

Atomic data needs

- Non-LTE models require a wealth of different atomic data
- The results can be **strongly sensitive to these atomic data**



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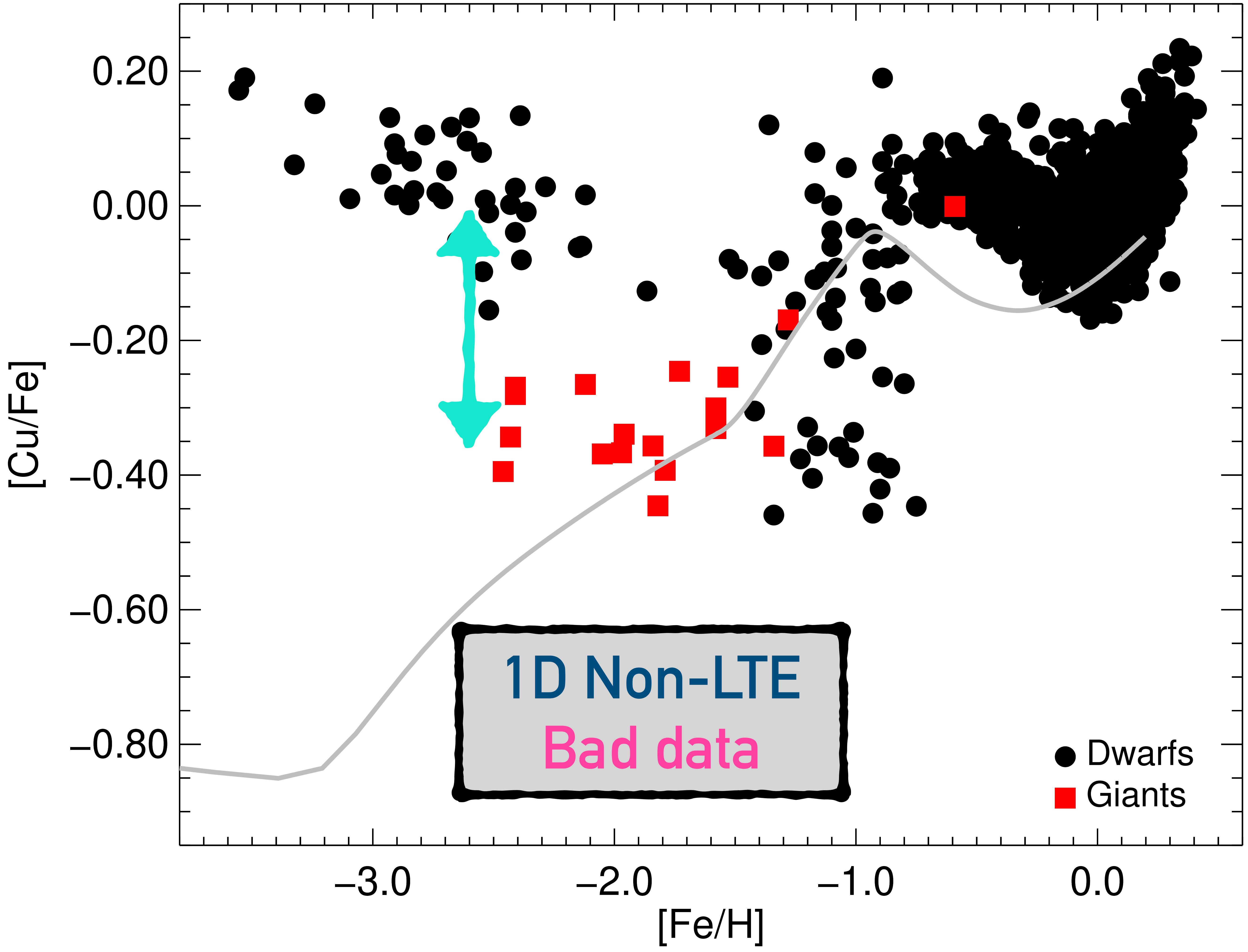
Atomic data needs

- Non-LTE models require a wealth of different atomic data
- The results can be **strongly sensitive to these atomic data**
- e.g. Copper with **alternative collisional data set** (Belyaev+ 2021): inconsistencies between **dwarfs** and **giants**; large line-to-line scatter



[Caliskan et al. 2025]

Case study: silver

- Most heavy neutrals have **never been studied in non-LTE** due to a lack of atomic data
- Ongoing work to rectify this, starting with **neutral silver** (UU/MAU/SU collaboration)

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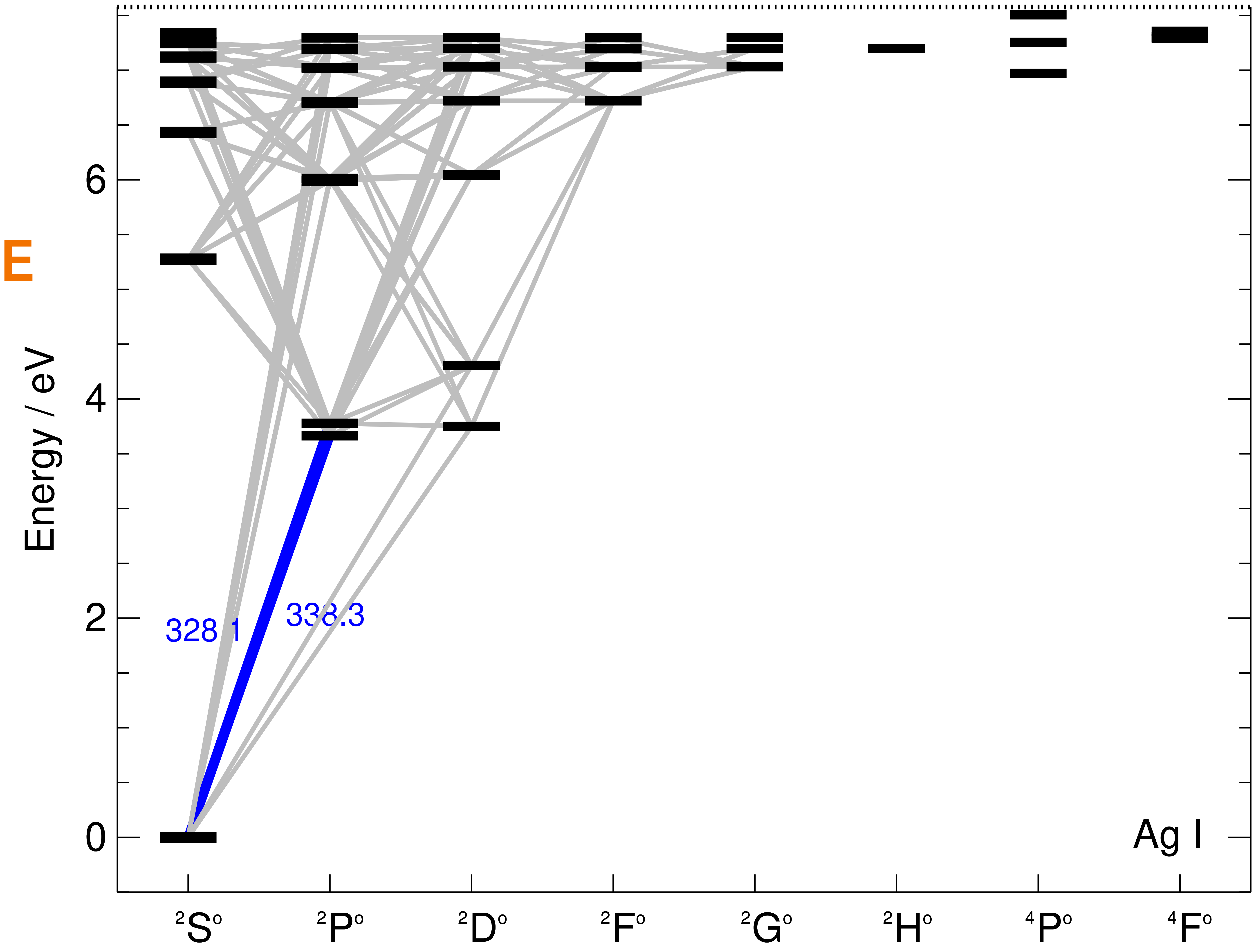
- **Energies** (NIST is OK for neutral Ag; for other heavies, can be incomplete)



[Caliskan et al. In prep.]

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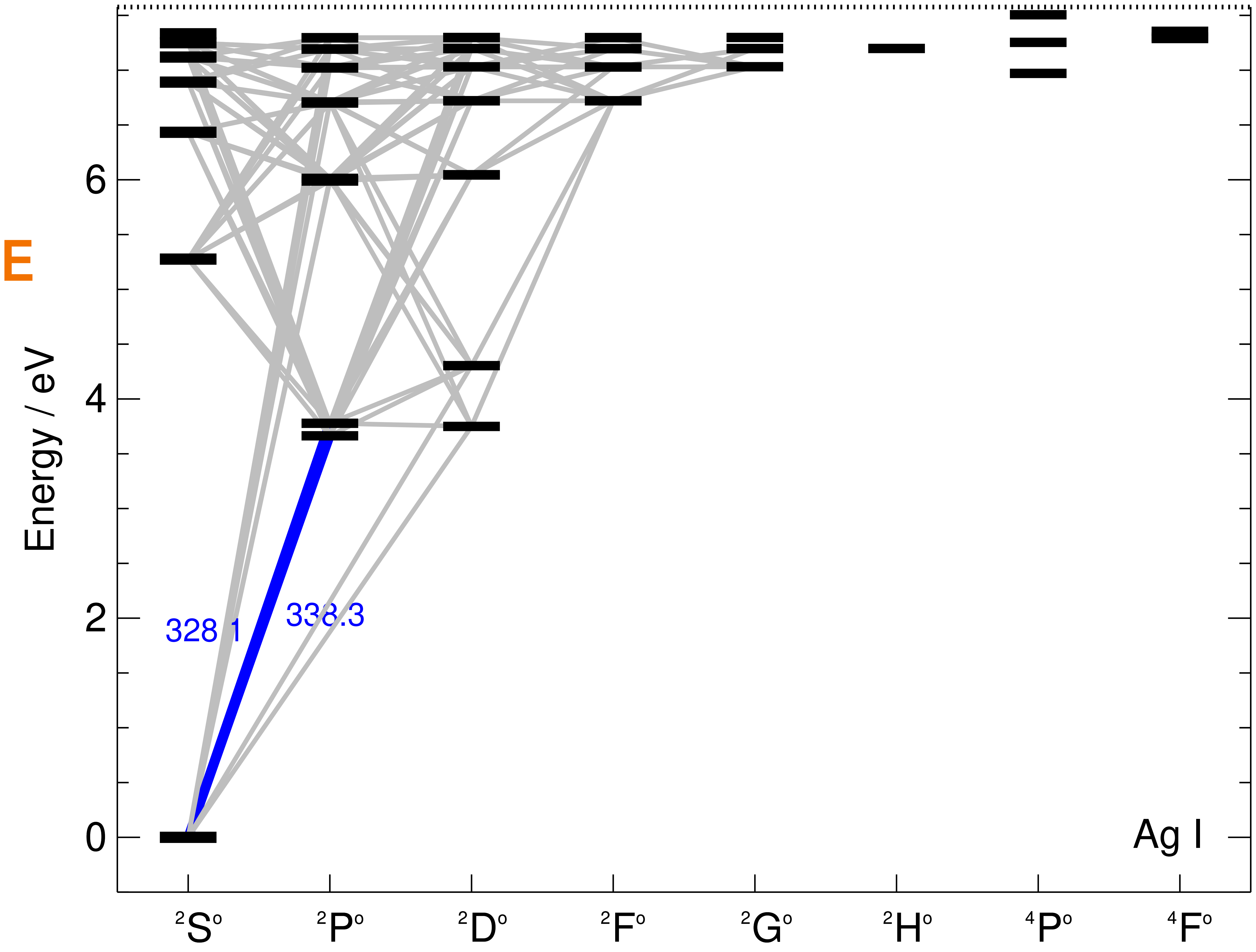
- **BB radiative transition rates** (Per Jönsson, MaU, *GRASP*)



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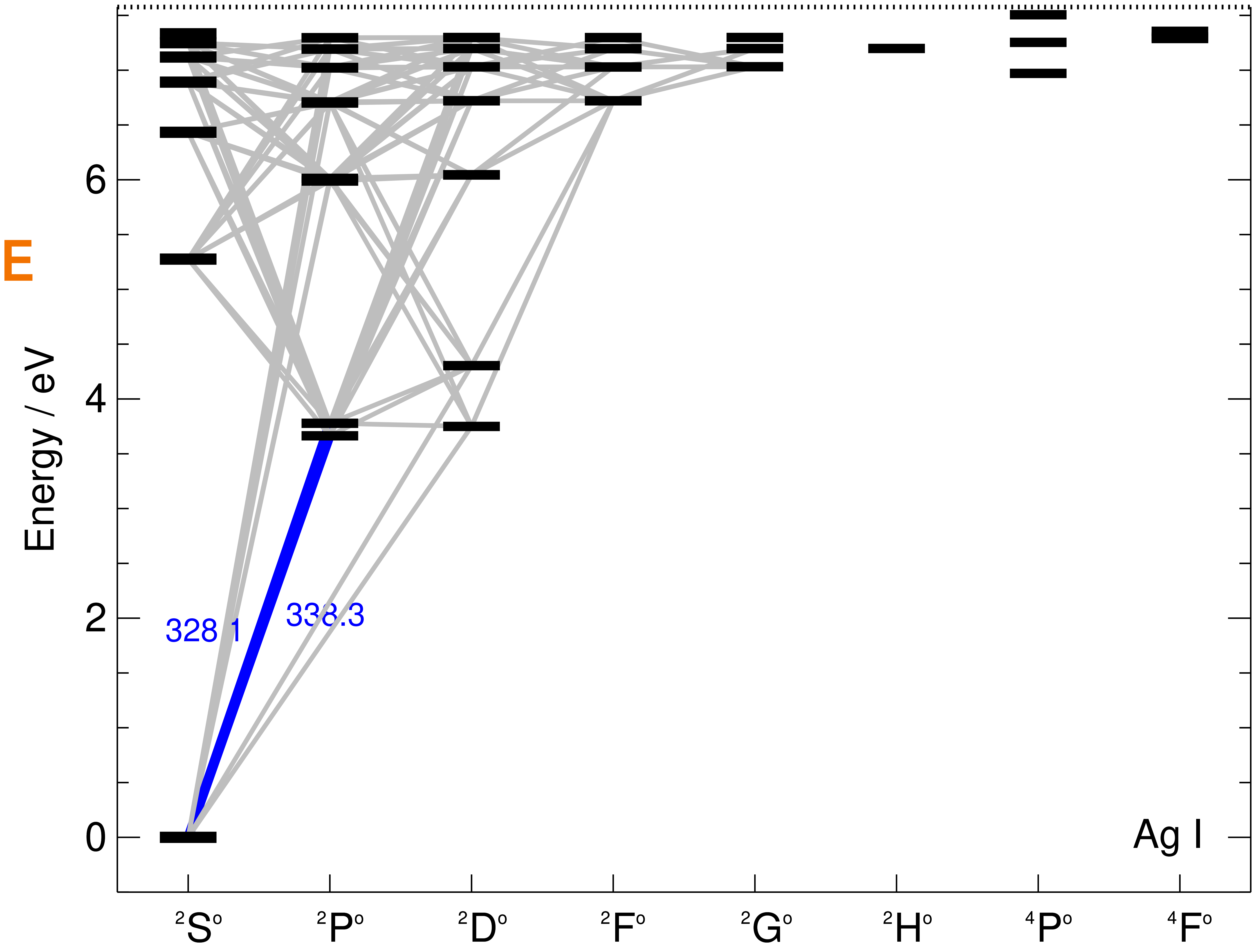
- **BF photoionisations** (Smaranika Banerjee, SU, *HULLAC*)



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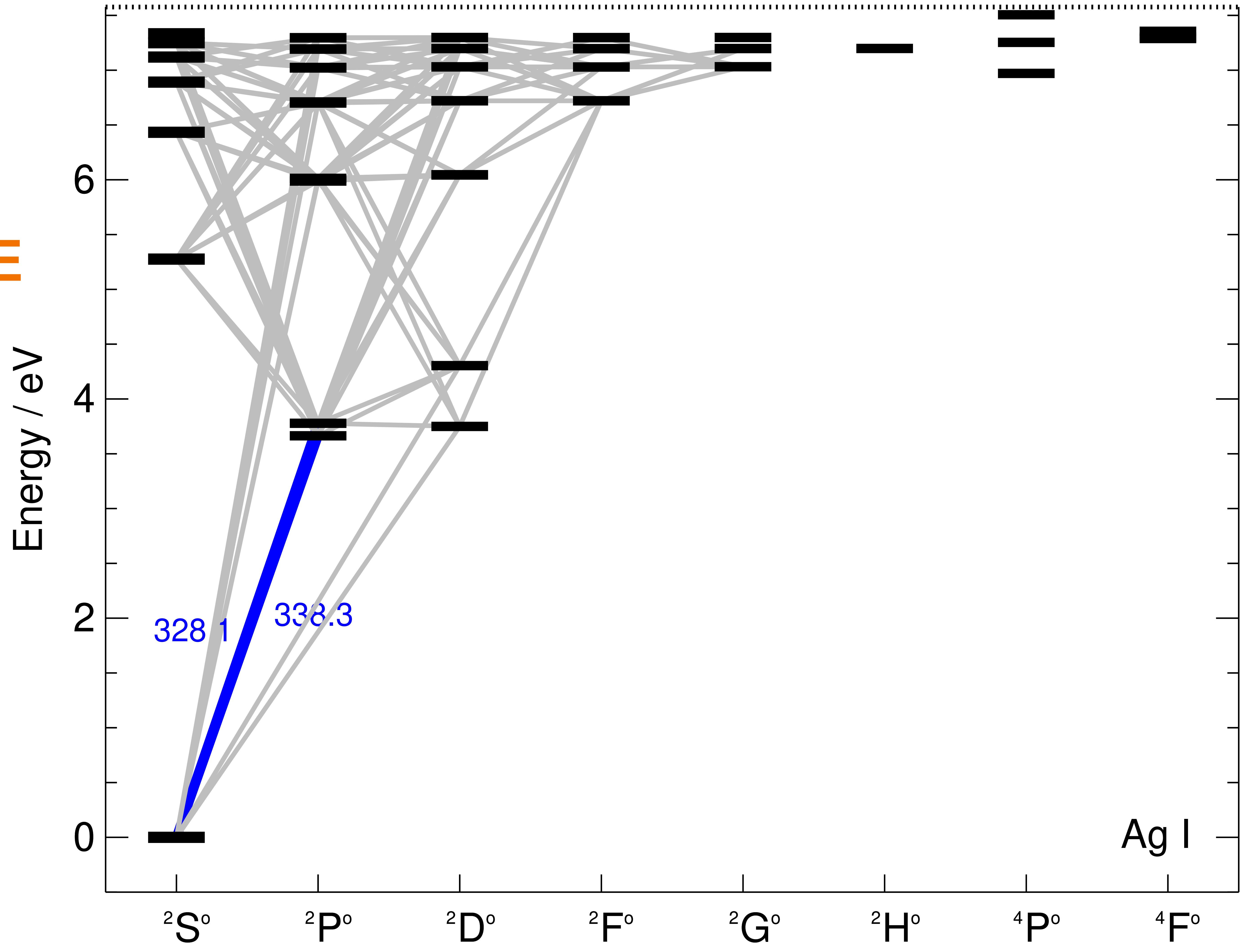
- **Inelastic Ag + e collisions and Ag + H collisions** (Sema Caliskan, UU, *various codes*)



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Case study: silver

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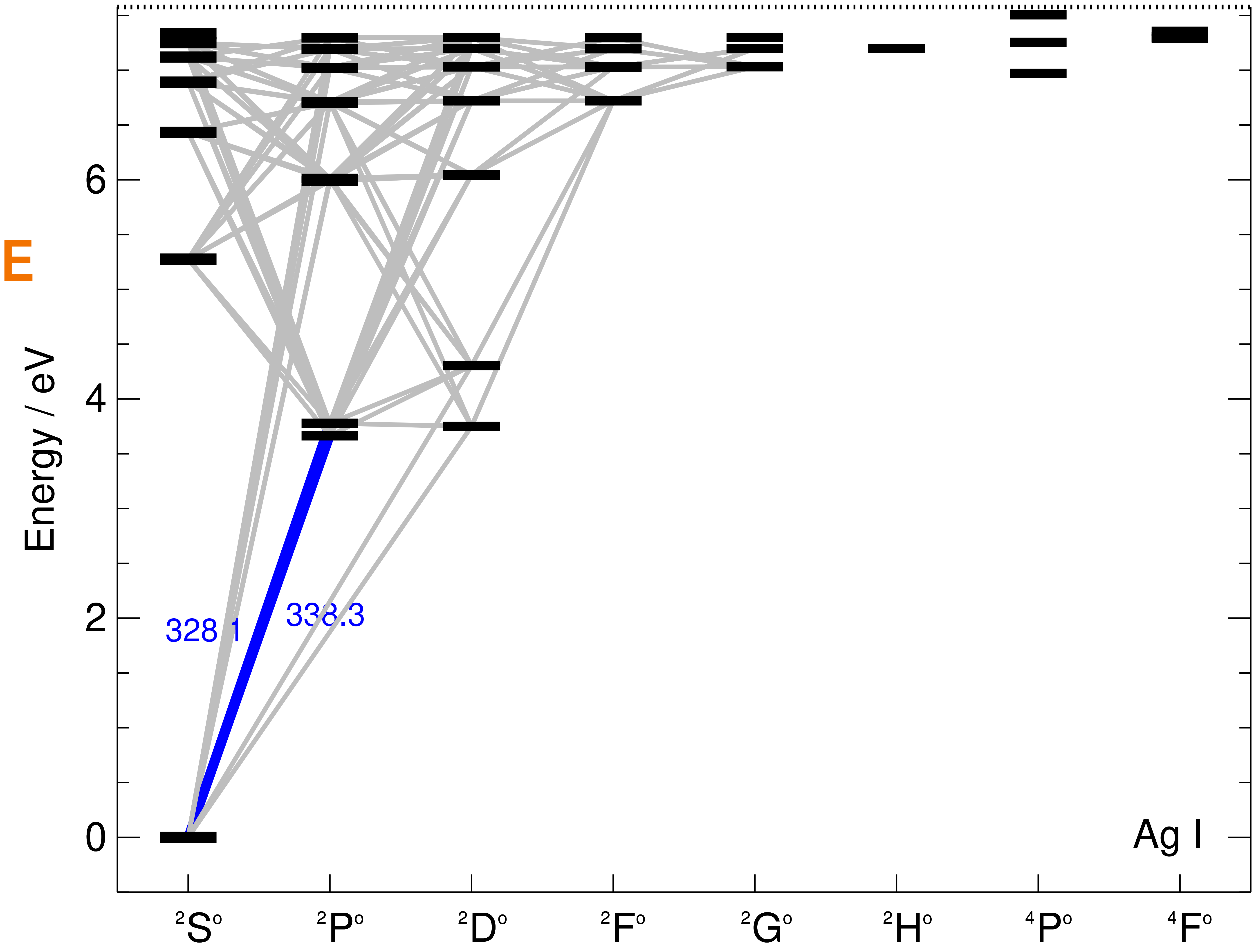
- **1D/3D non-LTE radiative transfer** (Sema Caliskan, UU, *Balder*)



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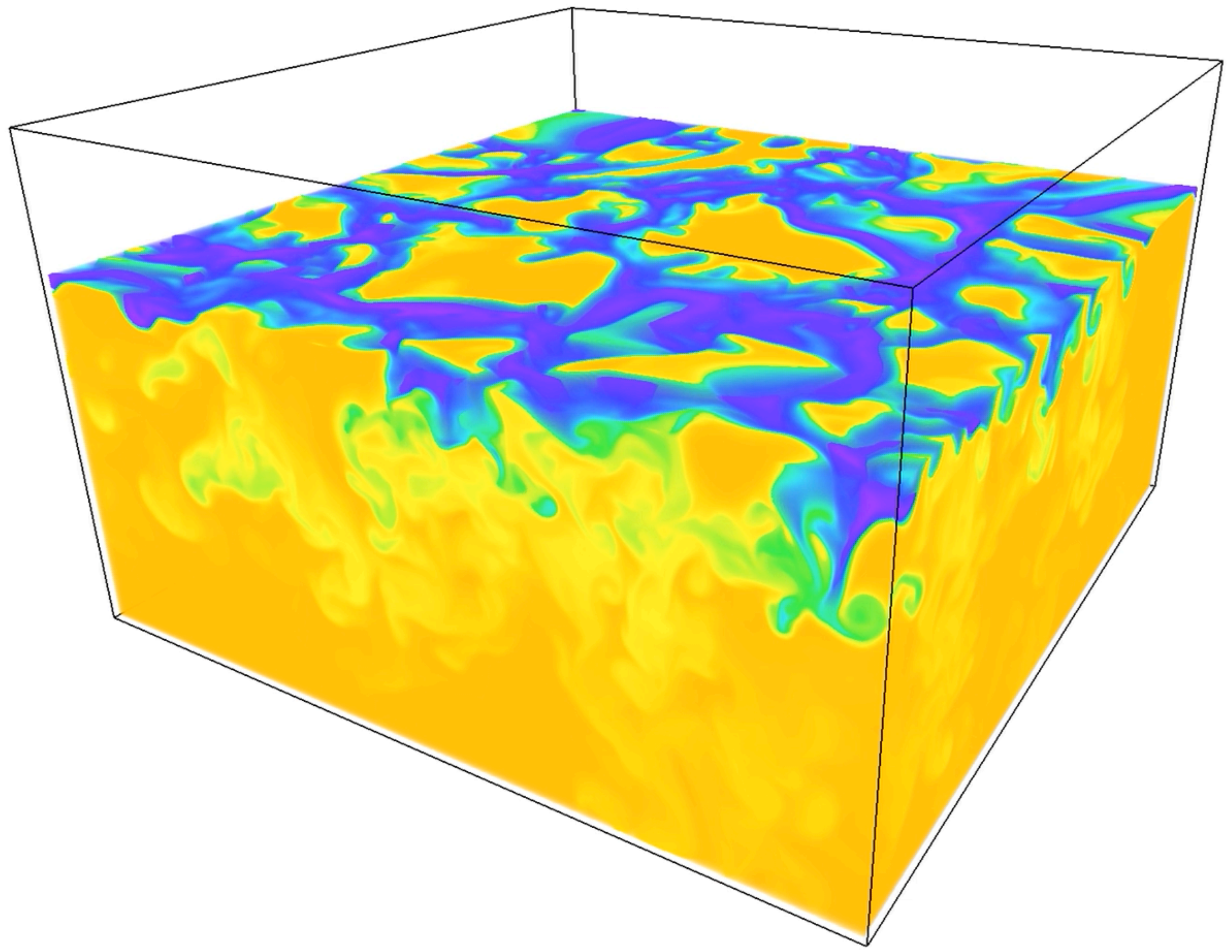
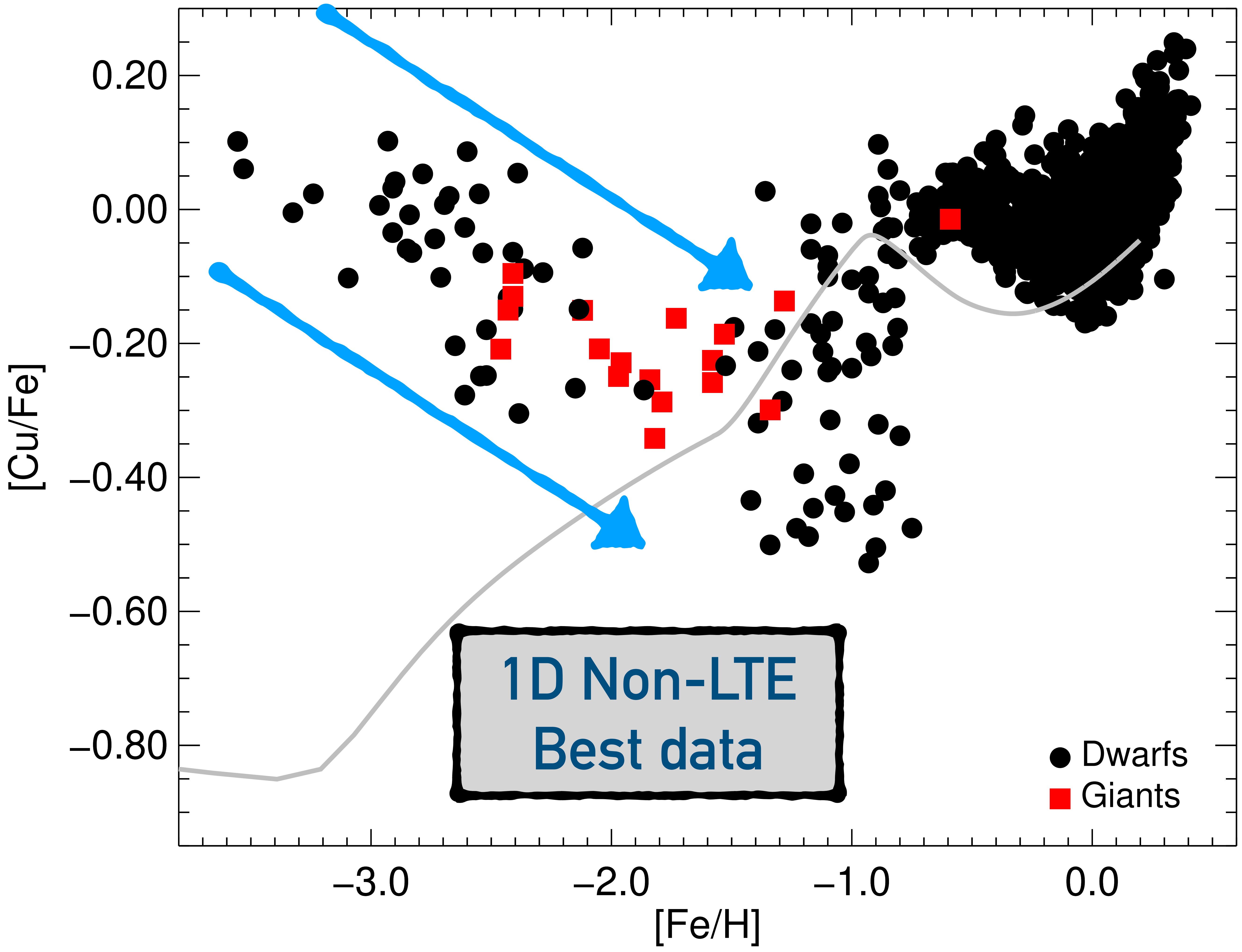
Conclusion

- Non-LTE modelling of stellar spectra **reveals new astrophysics**





Conclusion

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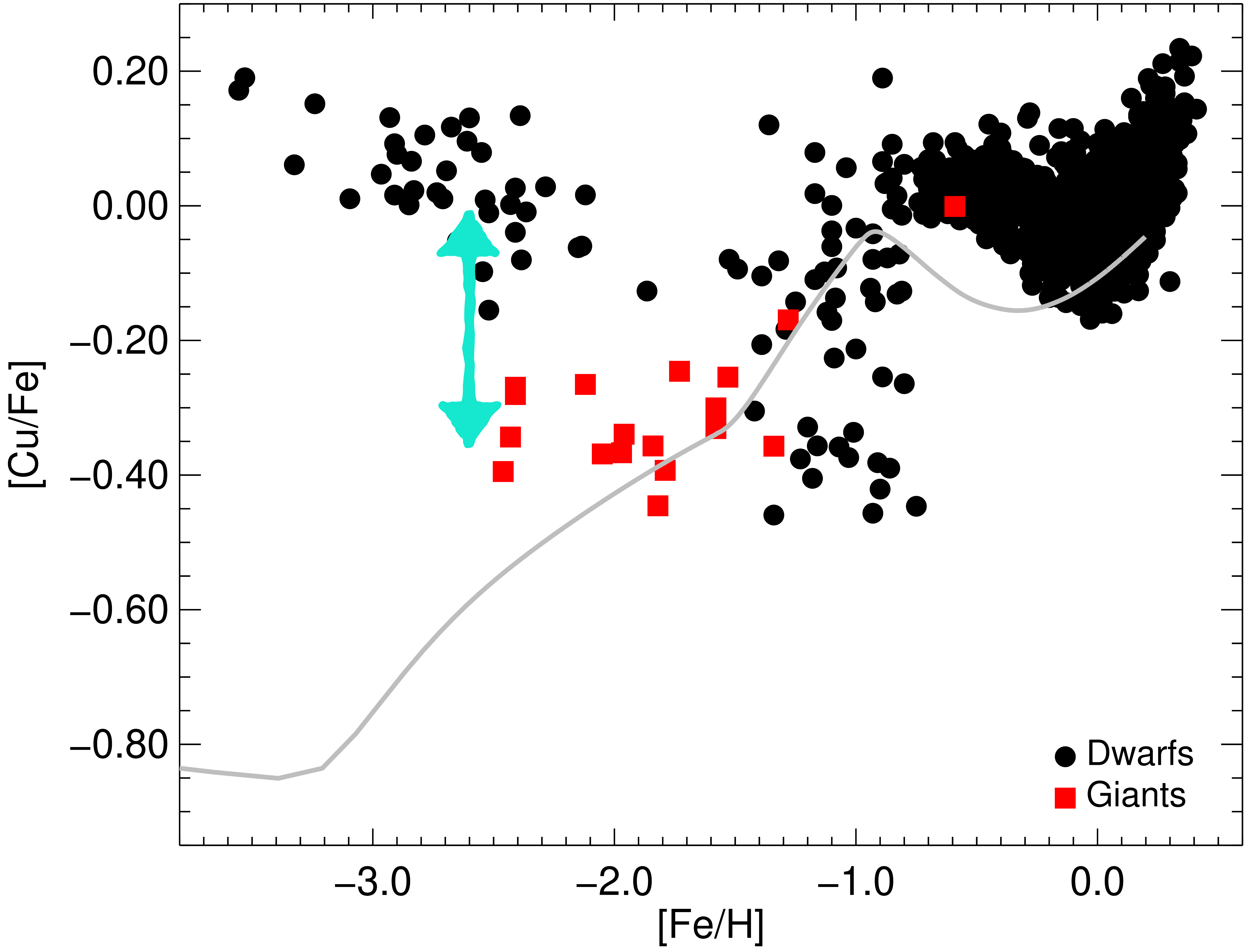
- Poor atomic data can make non-LTE analyses unreliable
- Lack of quality atomic data for neutrals hinders progress



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- Need **complete** energies, Einstein A's, photoionisations, inelastic collision cross-sections