Non-LTE iron abundances in cool stars: The role of hydrogen collisions

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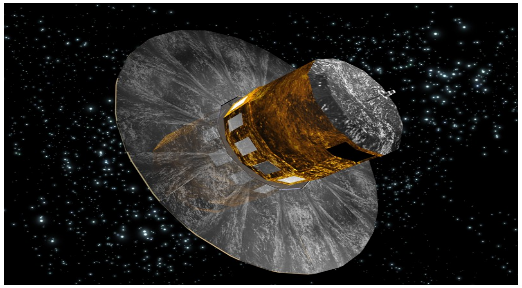
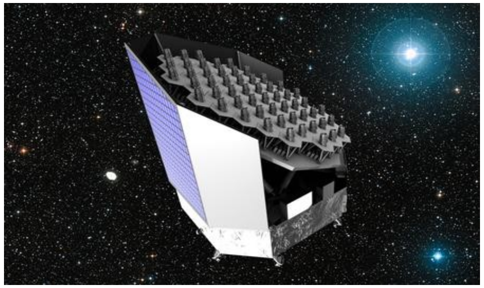
Iron line formation & abundance: Quite important!

Large-scale surveys (current + upcoming):
GAIA-ESO ,CoRoT, PLATO, ...

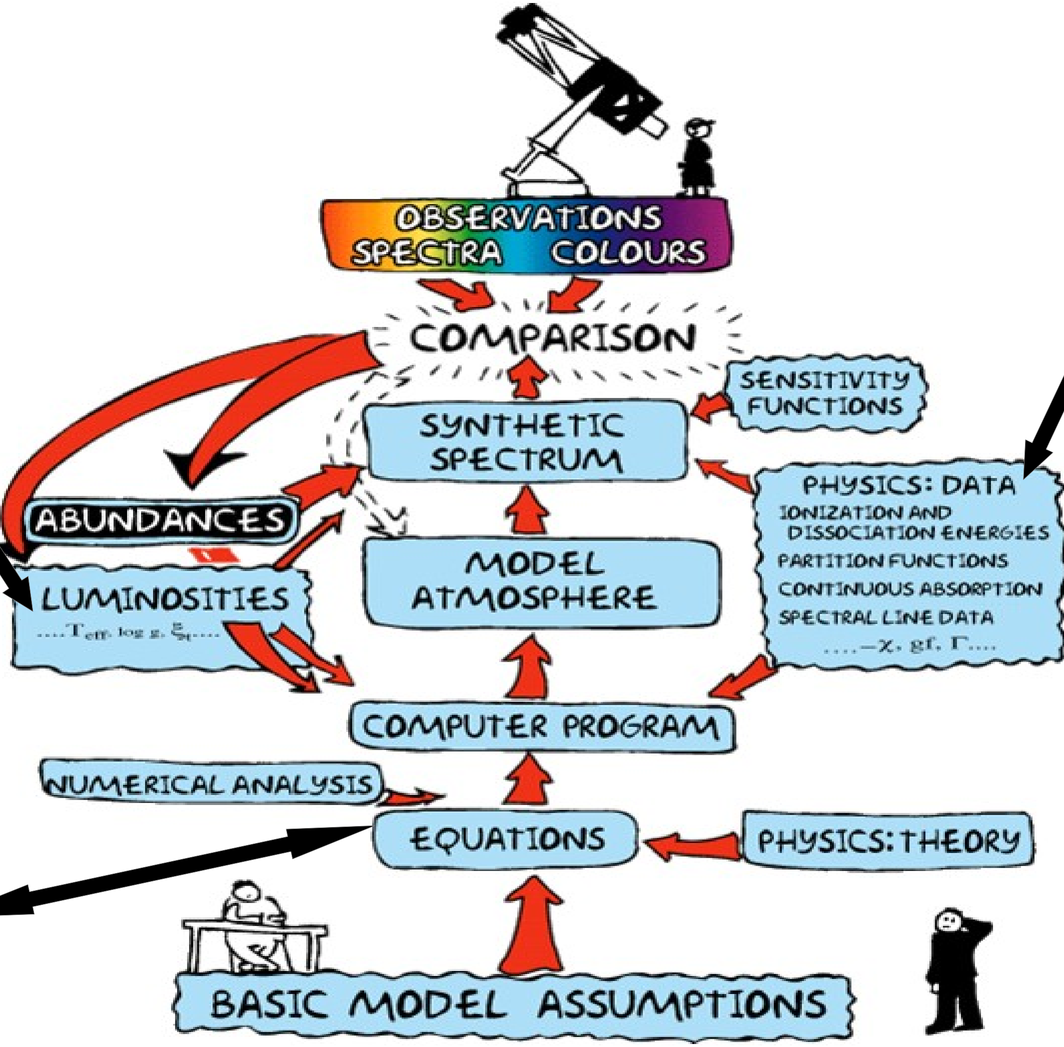
- Chemical evolution of the Galaxy
- Proxy of total metal content in stars ~ [Fe/H]
- Determination of fundamental atmospheric parameters





Abundace determination:

Different input atmospheric stellar parameters can provide different accuracies in the obtained abundances



Gustafsson (2009)

Non-LTE: Quantum calculations needed. Situation for radiative transitions (***f***, ***σ***) (TOP BASE,NIST,KALD,..) ahead of collisional transitions for most elements.

LTE, non-LTE, 1D, 3D

- Two main impact perturbers play the important role of collisions in cool stars: Electrons & neutral Hydrogen atoms (Plaskett, 1955)

- Even though the collisional frequency of electrons is higher: $v_e/v_H = (m_H/m_e)^{1/2}$, however for transitional energies < 4eV hydrogen collisions dominate *(Anderson 1981; Lambert 1993)*

- In addition, $n_H/n_e \sim 10^4$ esp. for metal poor stars
  - → Inclusion of H collisions quite important for better models!

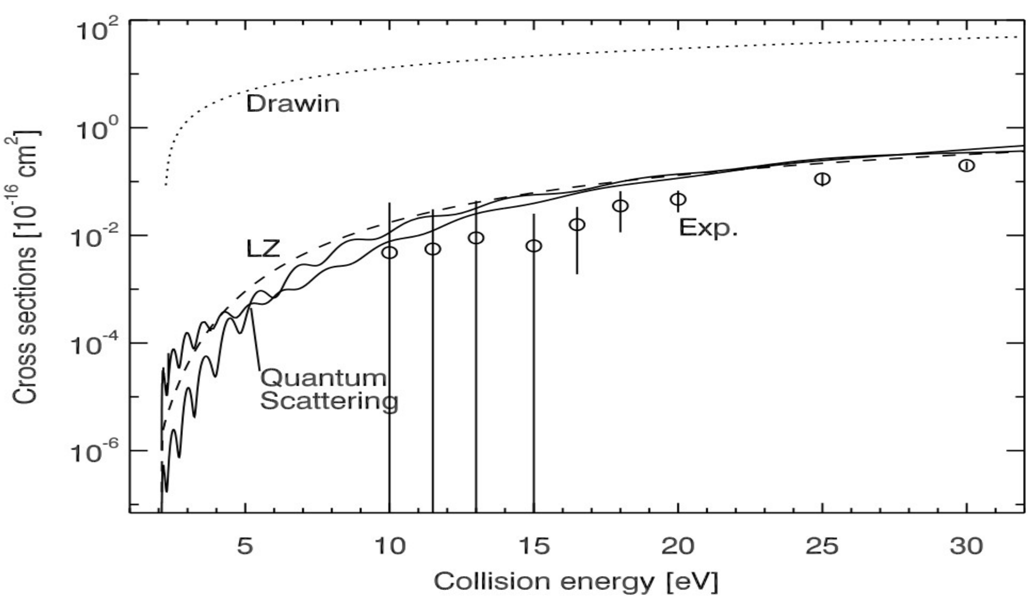
Status Quo?

→ For electrons, more quantum cross-sections being calculated for more atoms, including Fe (IRON Project: Zhang & Pradhan, (1995,1997), Pelan et al. 1997)

For H collisions, quantum cross sections exist only for a few atoms (Li,Na,Al,Mg,Si) (Belyaev, Barklem et al. 2003,2011,2012,2013,2014)

but none for Fe (yet! Soon?)

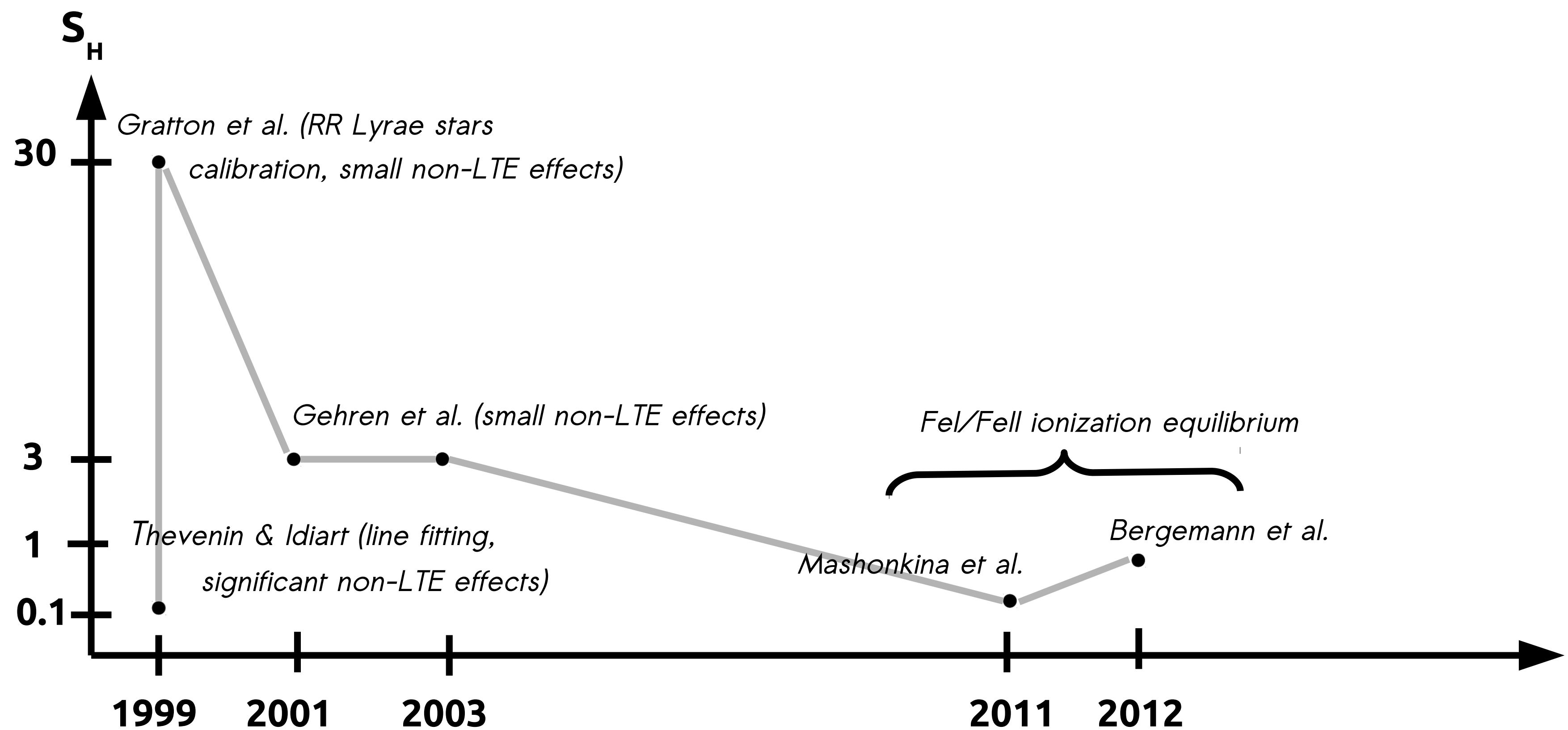
- Lack of Quantum data ~ tendency for approximations ⇒ hold uncertainties.
- Drawin (1968,1969) approx. recipe written for A + A → A + A collisions derived from Thompson (1912) for *e-* + A collisional cross sections.
- Rewritten by Steenbock & Holweger (1985) for A + H → A + H collisions.
- Shown to overestimate quantum calculations by orders of magnitude.



Barklem (2011), Na(3s) + H → Na(3s) + H collisional cross-sections: Drawin vs. Quantum vs. experimental data.

The Curious case of Hydrogen collisions:

→ A global scaling fudge factor S_H is applied to fit the observations. Different values have been implied from different fitting methods for Fe:



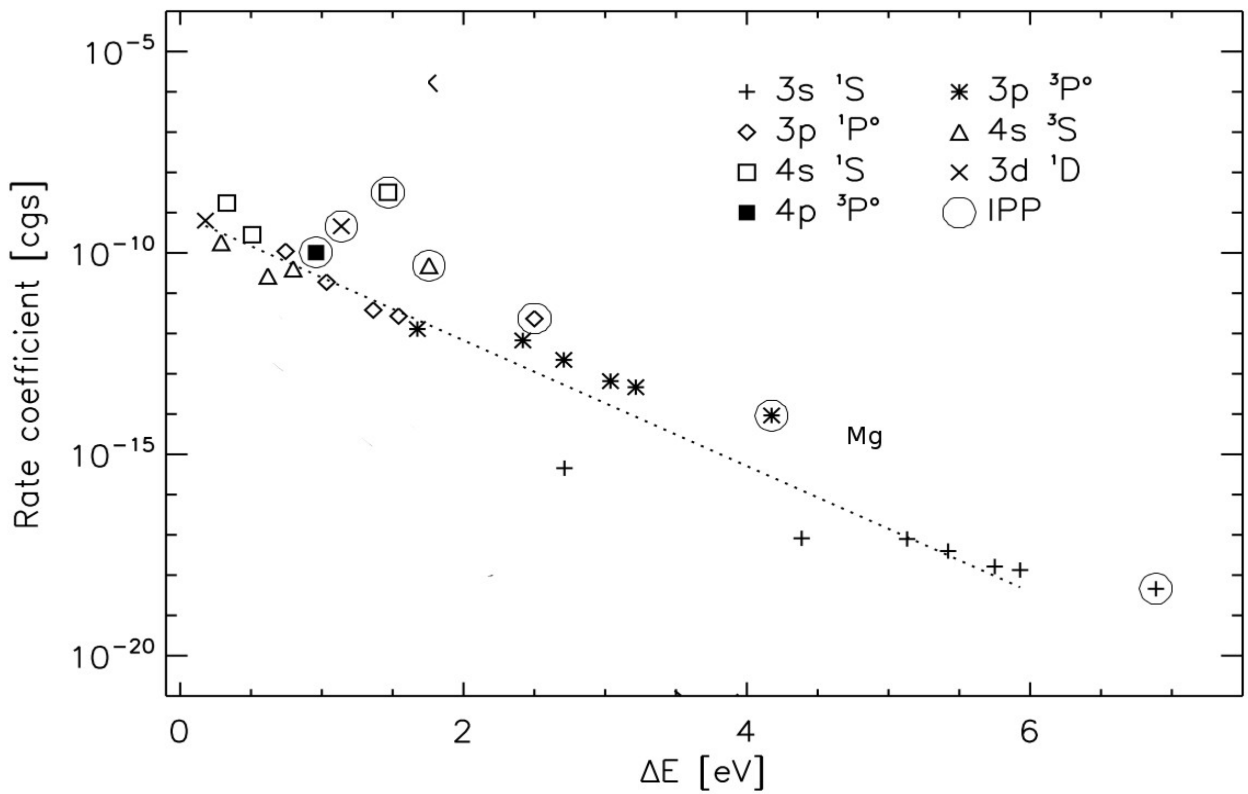
Different methods, model atoms, stars → Different S_H values.

So Whats new?

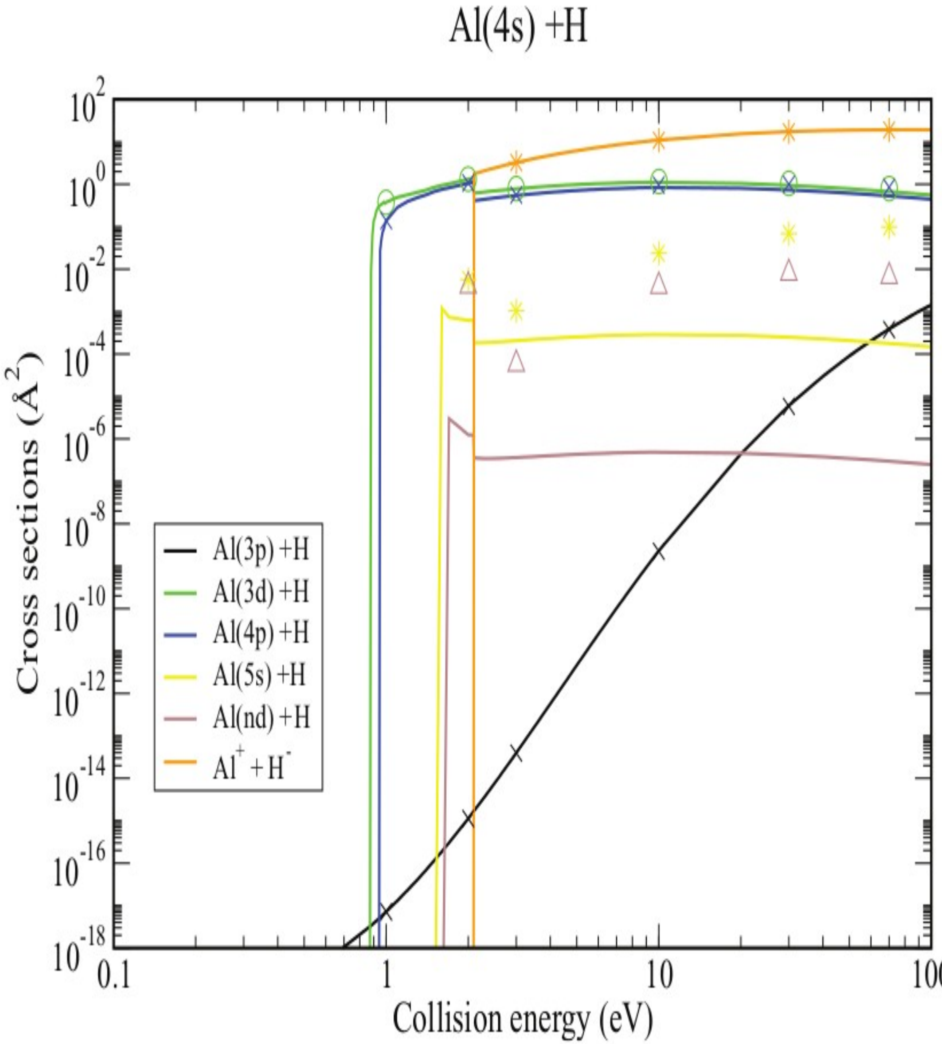
Recent quantum calculation show domination of charge exchange of atoms with neutral H : $A + H \longrightarrow A^{+} + H^{-}$

(Belyaev, Barklem et al. 2003,2011,2012,2013,2014)

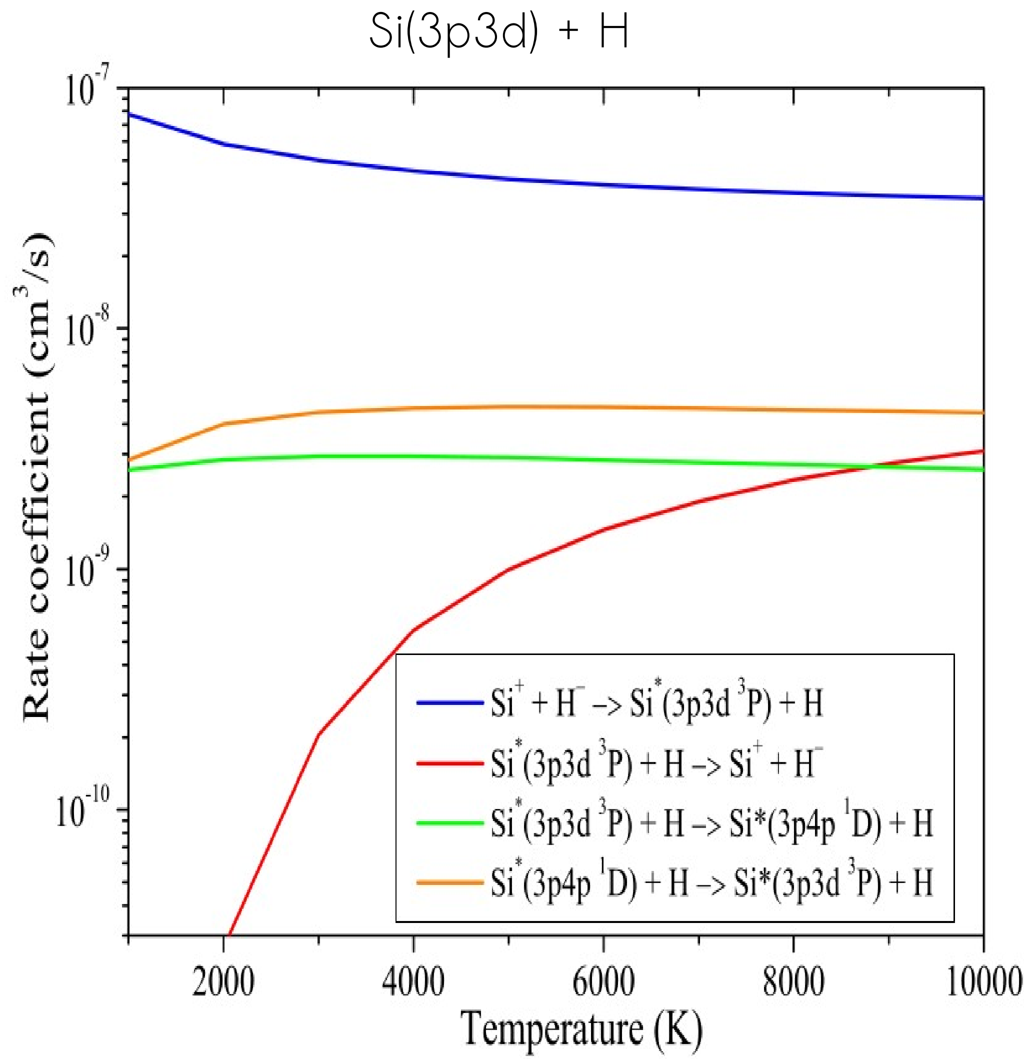
- Mg + H rate coeffs. For collisional transitions from different states.
- Ion-pair production (charge exchange) dominate the collisional processes



Barklem et al. (2012)



Belyaev (2013)



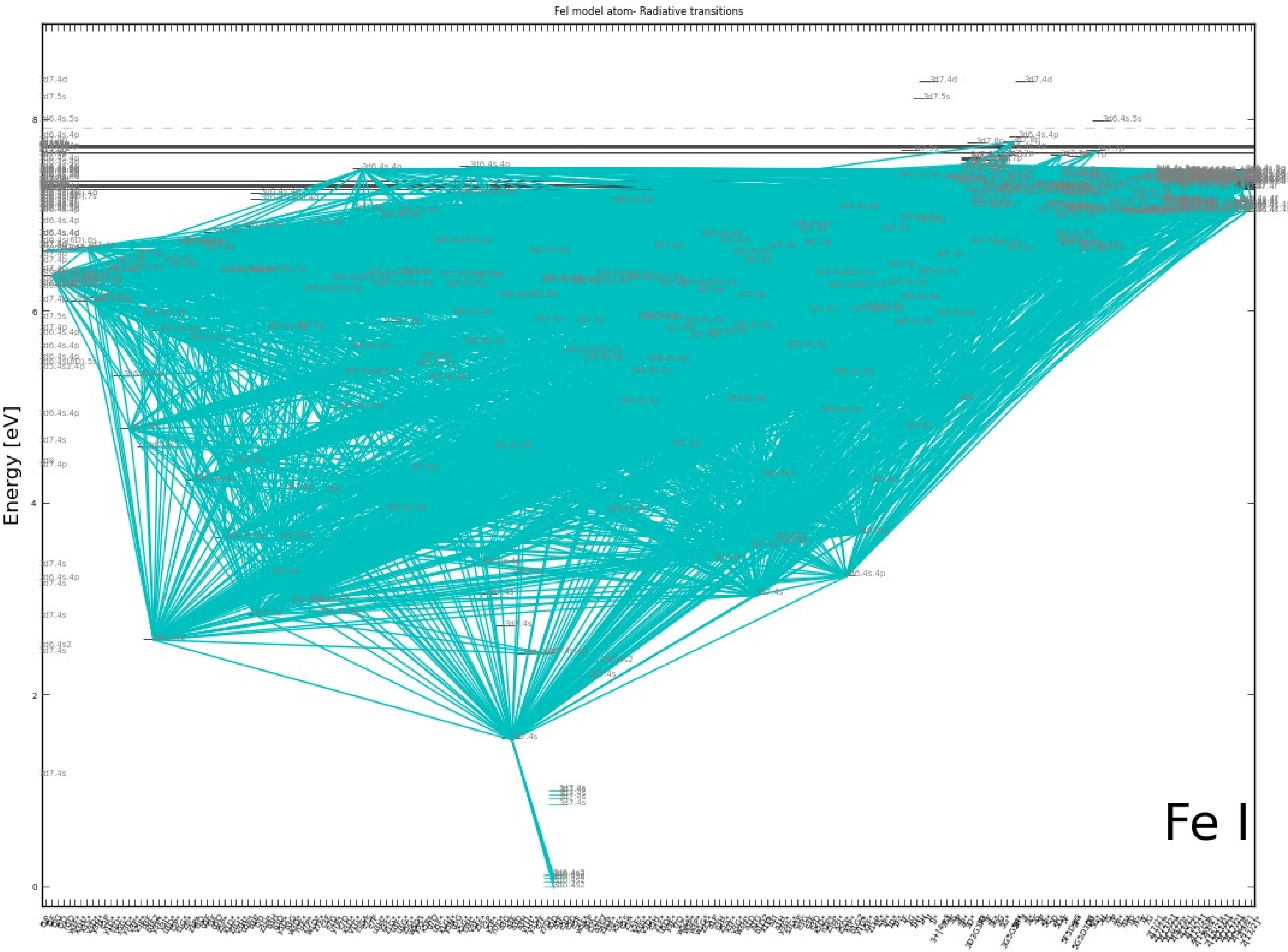
Belyaev et al. (2014)

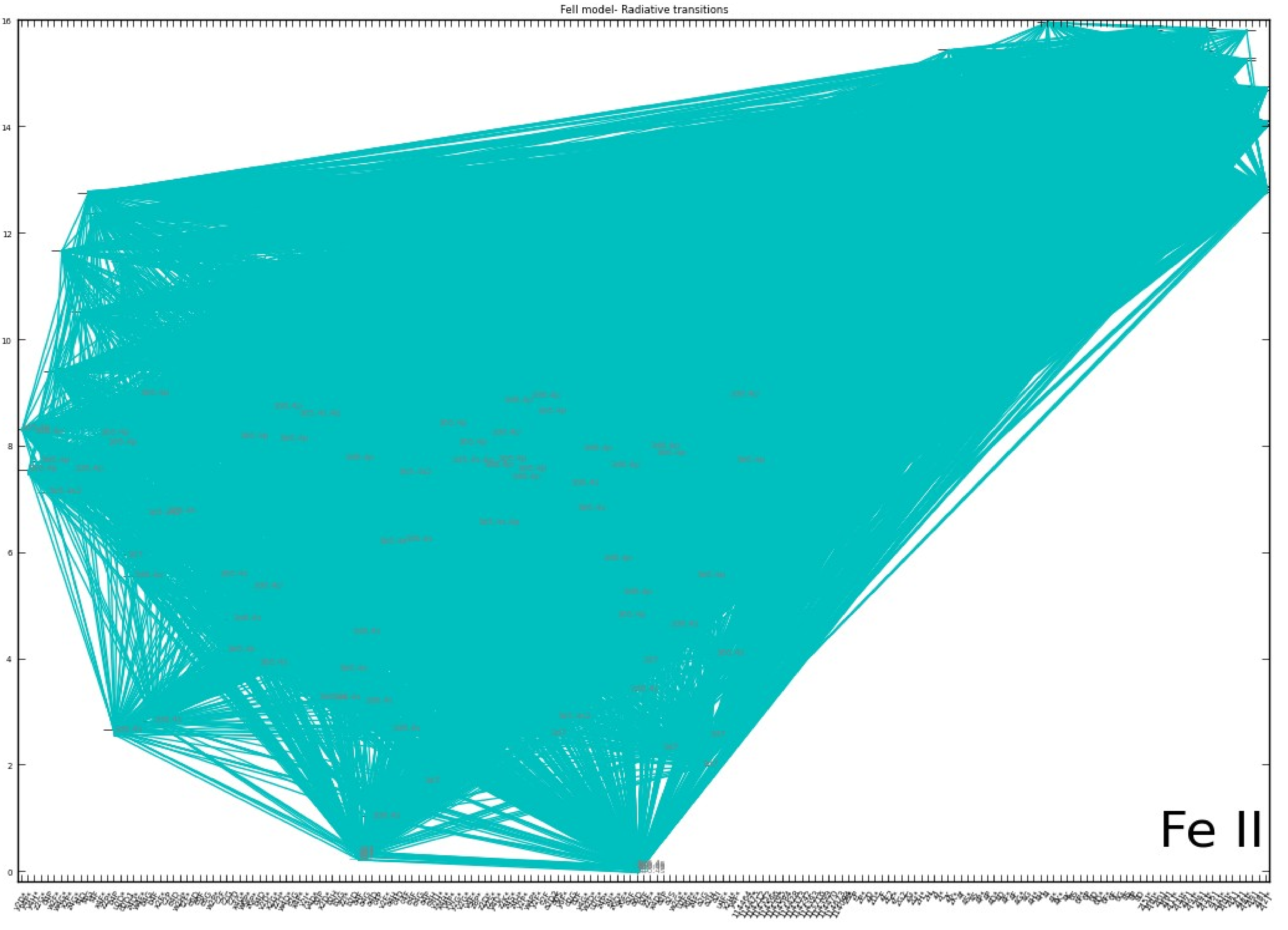
→ Same has been shown for Al & Si & ...

Question: What is the role of charge exchange with Iron + H?

Method:

- Built rather complete FeI/FeII model atom including most up-to-date radiative and collisional atomic data (when available) from atomic databases: NIST,VALD,KALD,TOPBASE,NORAD, ...


FeI model atom- Radiative transitions
Energy [eV]
Fe I


FeII model- Radiative transitions
Fe II

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- Started from reliable atmospheric parameters, namely logg from asteroseismology, benchmark stars ...

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- Coupled all energy levels with electron & hydrogen collisions (excitation, ionization & charge exchange) a la Drawin scaled by different S_H values (globally) for each type of process.

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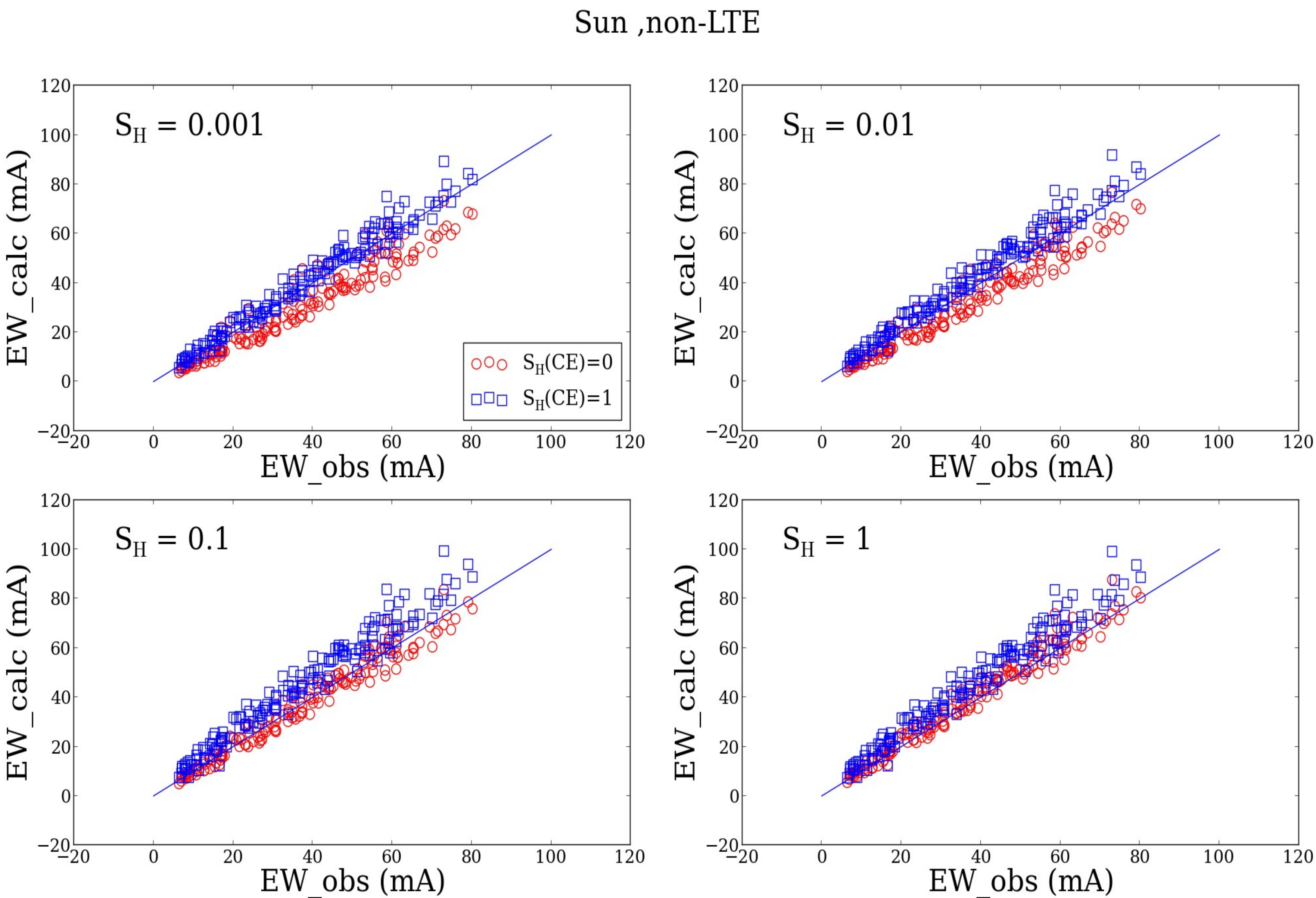
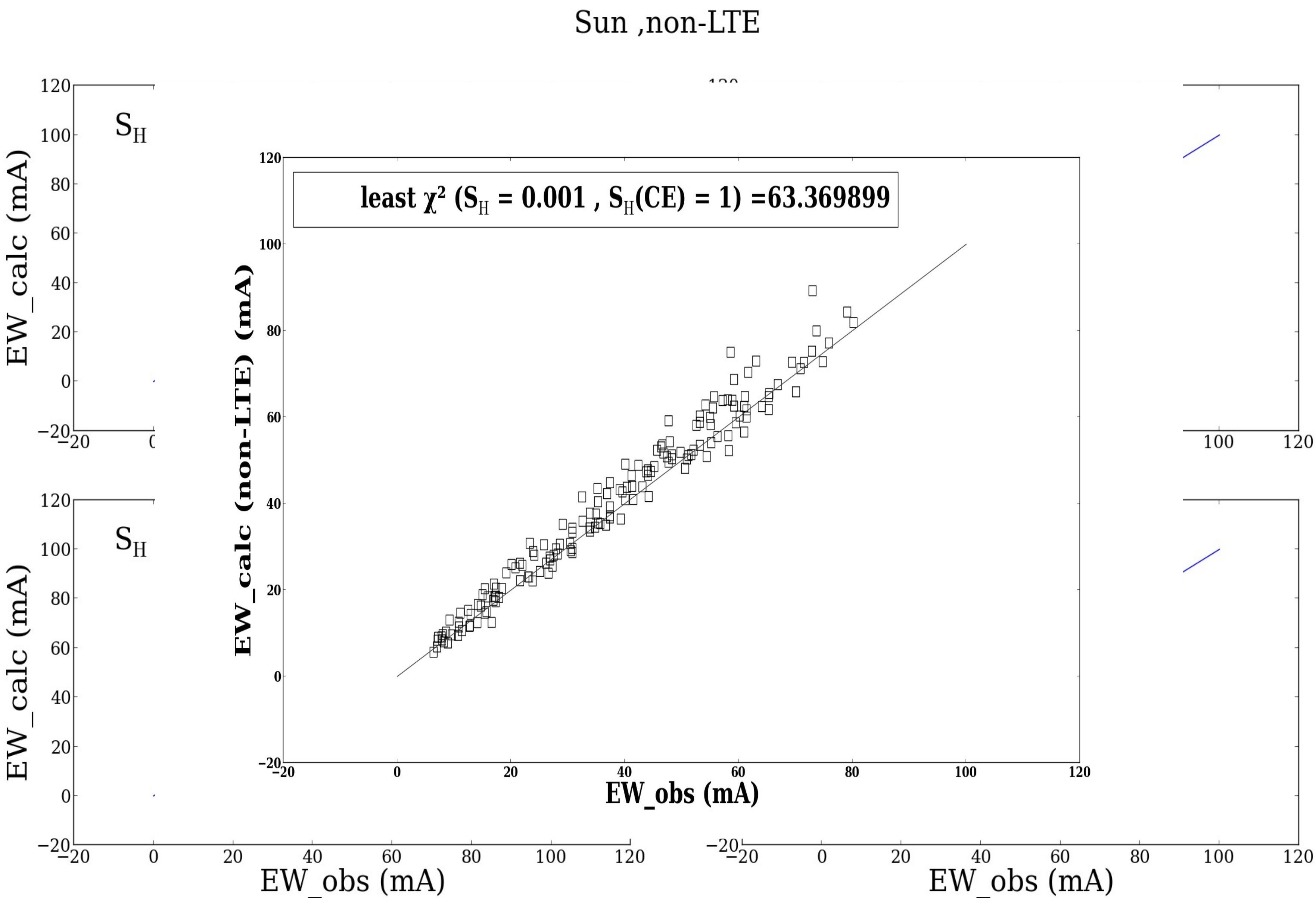
- Coupled all energy levels with hydrogen collisions (excitation, ionization & charge exchange) a la Drawin scaled by different S_H values (globally) for each type of process.

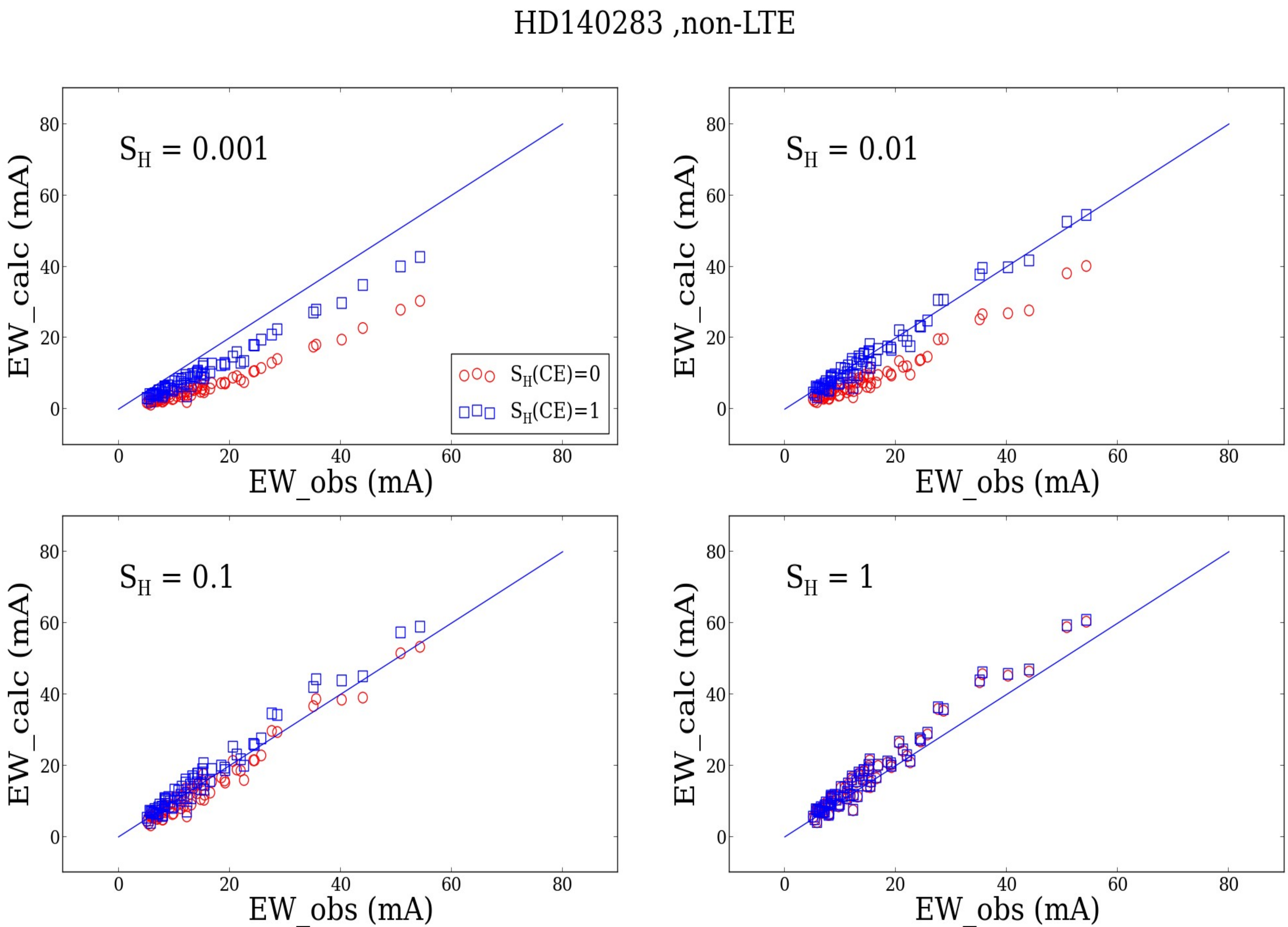
- Performed non-LTE calculations for all different models & compared with observed Equivalent widths EW(obs).



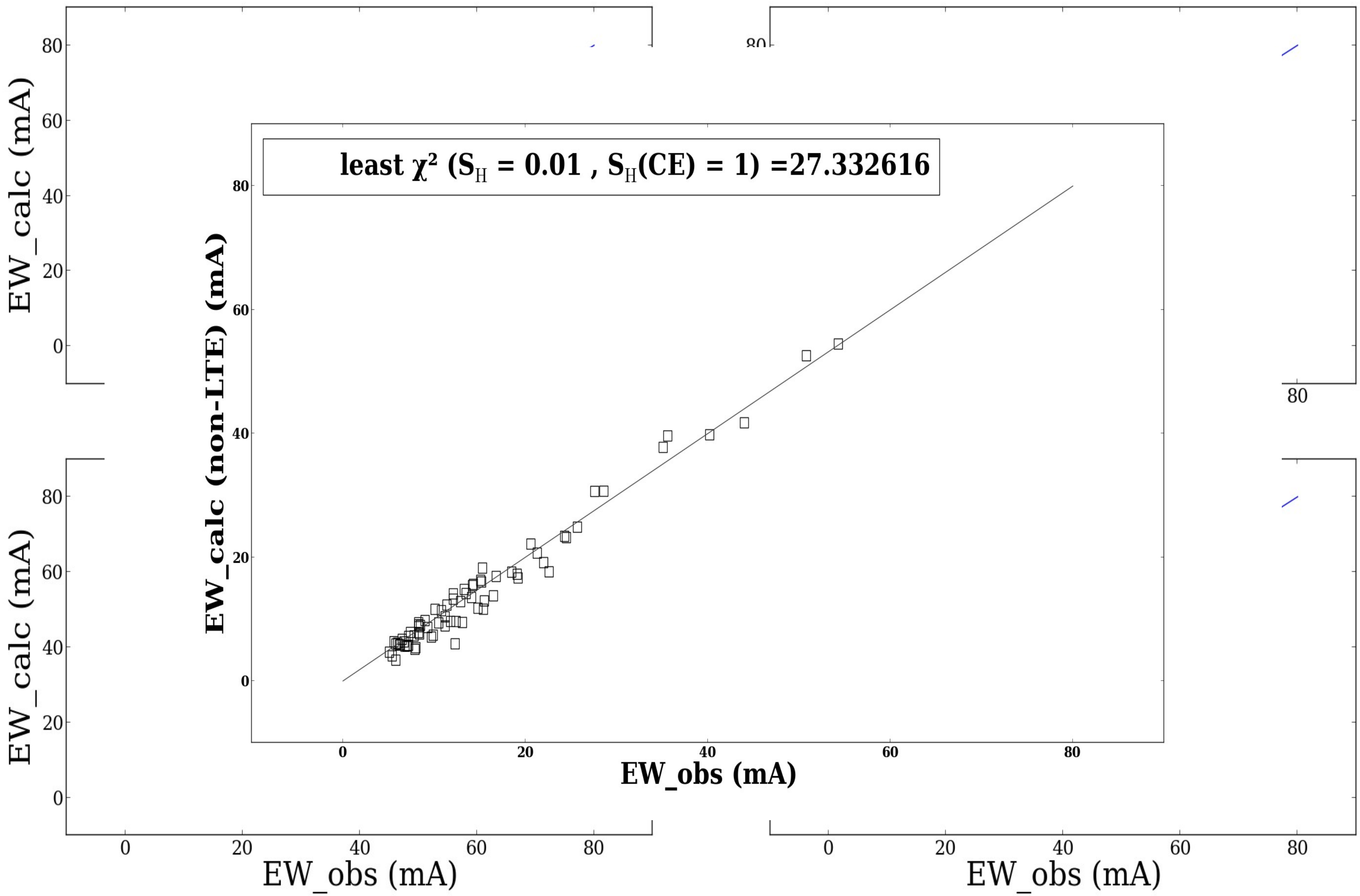
Sun ,non-LTE
S_H = 0.001
S_H = 0.01
S_H = 0.1
S_H = 1
S_H(CE)=0
S_H(CE)=1
EW_calc (mA)
EW_obs (mA)
−20
0
20
40
60
80
100
120



Sun ,non-LTE
least χ² (S_H = 0.001 , S_H(CE) = 1) =63.369899
EW_calc (non-LTE) (mA)
EW_obs (mA)
EW_calc (mA)
EW_calc (mA)
EW_obs (mA)
EW_obs (mA)
S_H
S_H


HD140283 ,non-LTE
S_H = 0.001
S_H = 0.01
S_H = 0.1
S_H = 1
S_H(CE)=0
S_H(CE)=1
EW_calc (mA)
EW_obs (mA)
0
20
40
60
80

HD140283 ,non-LTE



→ To confirm the method, we also did the same calculations for Silicon for which quantum rates for low energy levels excitations and charge exchange exist

→ EW(quantum) vs. EW(Drawin) for different S_H recipes

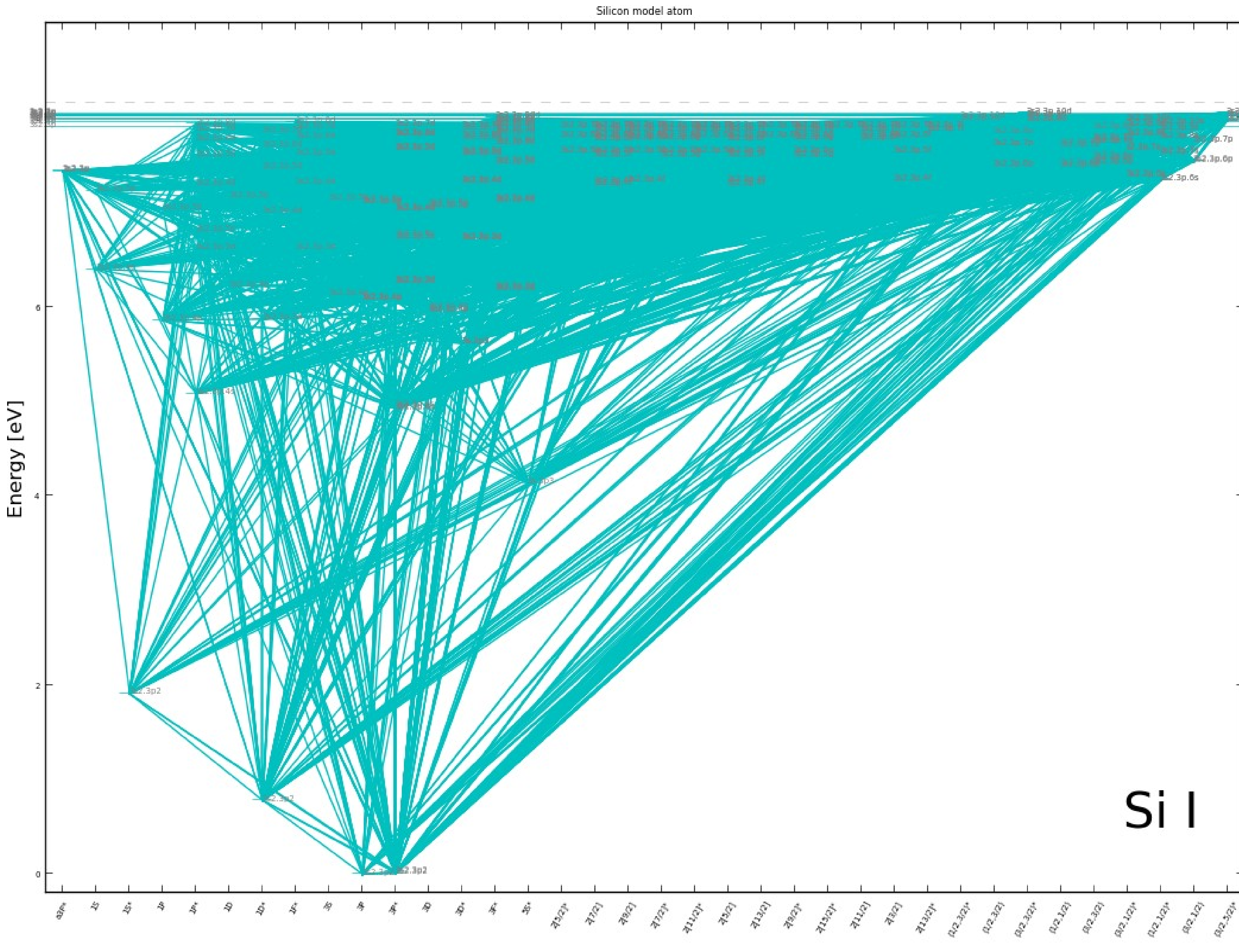
→ lines $1eV < \Delta E < 4eV$

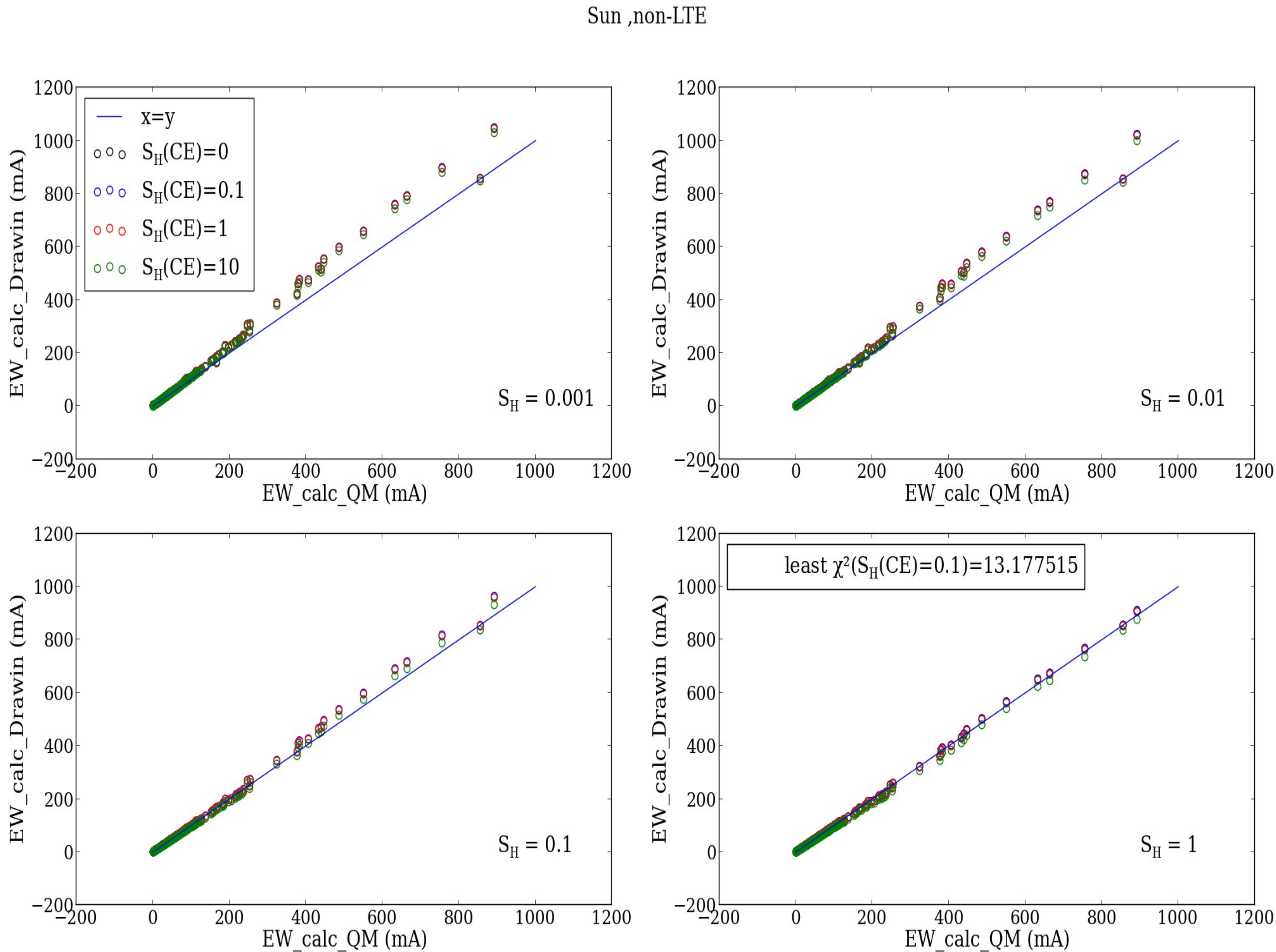
→ Benchmark stars

→ Built 2 Si I model atoms:

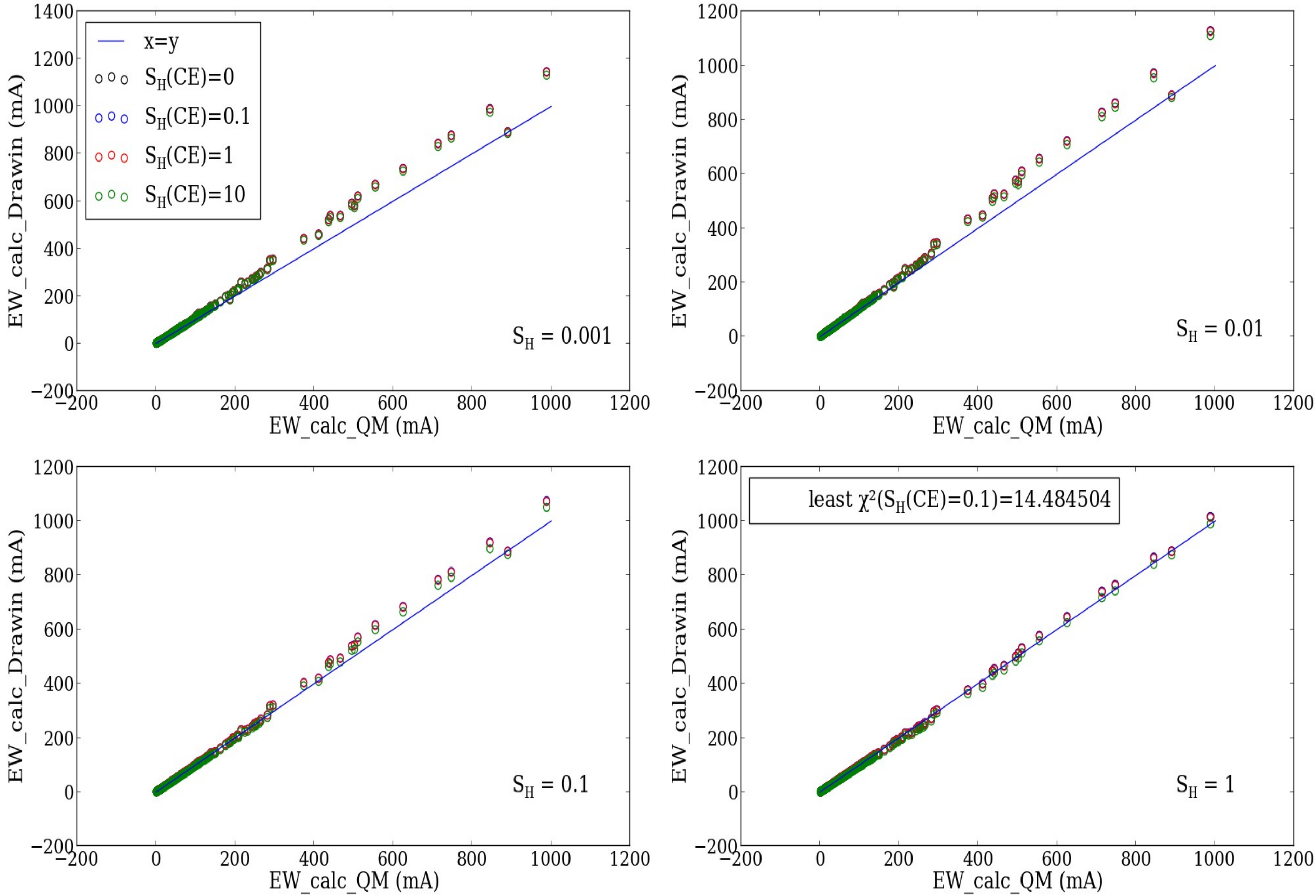
→ Quantum data for Hydrogen collisions & charge exchange (Belyaev et al. 2014)

→ Drawin approx. for Hydrogen collisions & charge exchange with different scaling factors

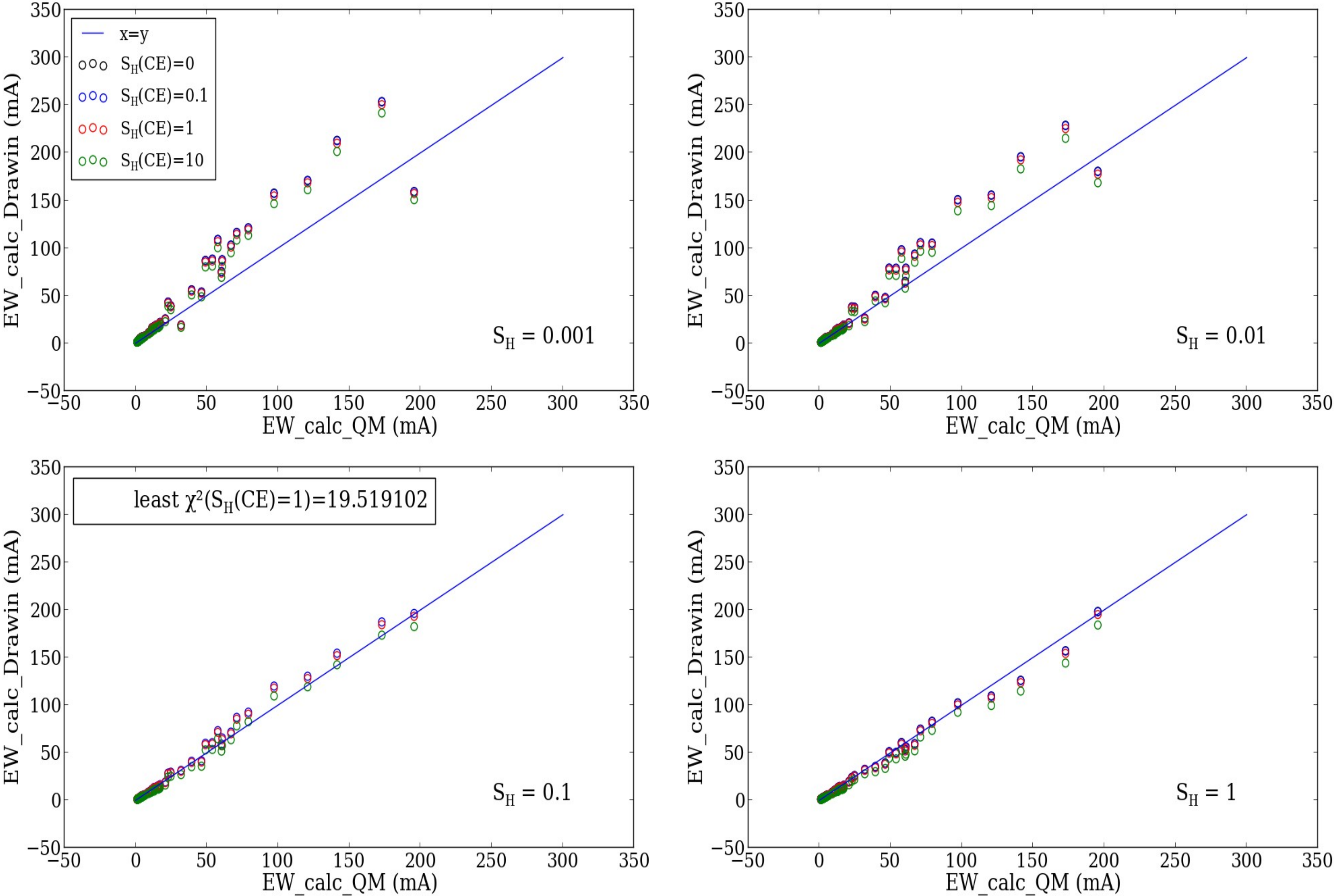

Silicon model atom
Energy [eV]
0
2
4
6
Si I


Sun ,non-LTE
x=y
S_H(CE)=0
S_H(CE)=0.1
S_H(CE)=1
S_H(CE)=10
S_H = 0.001
S_H = 0.01
S_H = 0.1
S_H = 1
least χ²(S_H(CE)=0.1)=13.177515
EW_calc_Drawin (mA)
EW_calc_QM (mA)

Alpha Centauri A (metal-rich main sequence star),non-LTE



HD140283 (metal poor Halo sub-giant),non-LTE



Large scale tests of our model:

→ Being part of the GES-CoRoT effort to derive accurate fundamental parameters of a large sample of stars (616) (UVES + GIRAFFE spectra).

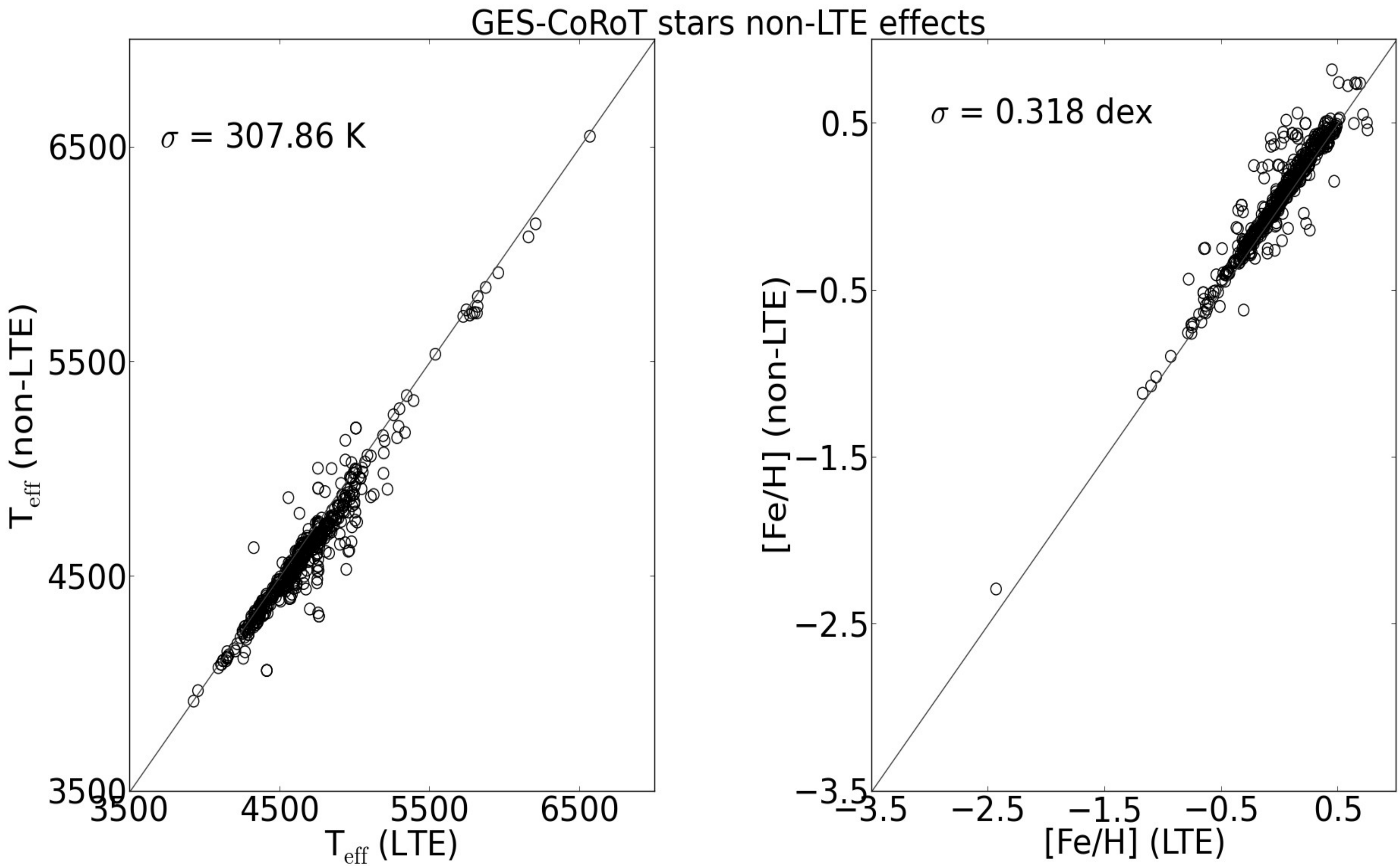
→ Calculated ~ 10,500 non-LTE models for a large grid of atmospheric parameters (MARCS atmosphere models):

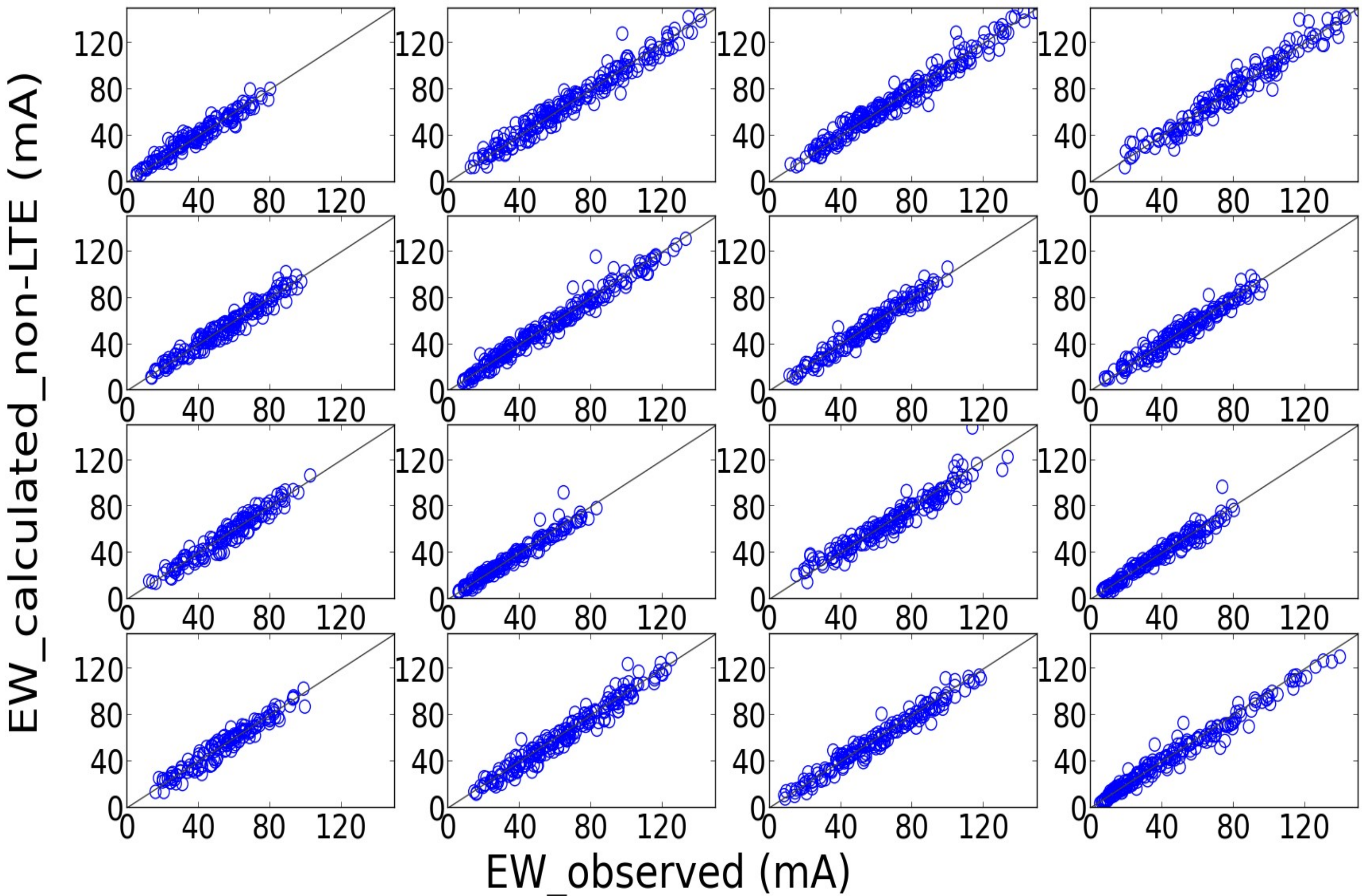
- Teff = [3500 , 7000], ΔE =250K
- Logg = [0.5 , 5], Δlogg = 0.5dex
- [Fe/H] = [-3.00 , +0.75], Δ[Fe/H]=0.25dex
- ξ_t = [0 , 5], $\Delta\xi_t$=1km/s

→ We wrote a robust multi-dimensional non-linear least fitting code based on the Levenberg-Marquardt algorithm.

→ Starting from asteroseismic log*g*, derived non-LTE / LTE Teff, [Fe/H] & microturbulent velocities ξ_t by least χ^2 fitting observed EW to calculated EW.

Ges-CoRoT Results:




EW_calculated_non-LTE (mA)
EW_observed (mA)
0
40
80
120

Conclusions:

→ Hydrogen collisions play an important role in Fe line formation.

→ We have shown that charge exchange of Fe + H → $Fe^+ + H^-$ dominates over the hydrogen processes, thus in accordance with quantum calculations obtained for other elements.

→ The tests of our model (including charge exchange) proved consistent in deriving atmospheric parameters for a large sample of stars (GES-CoRoT).

Perspectives:

→ Energy dependent S_H for the dominant charge exchange.

→ Include 3D effects, convection.

→ Inclusion of quantum cross-sections for Fe + H once calculated.

Thank you

for your very kind attention!