The Impact of 1D and 3D NLTE Effects on neutron-capture elements

Nick Storm

Maria Bergemann's "Stellar spectroscopy and stellar populations"

MPIA, Heidelberg, Germany

17th International Symposium on Nuclei in the Cosmos, Daejeon, Korea

19 September 2023

What is NLTE?

- Non-local thermal equilibrium (Non-LTE)

What is NLTE?

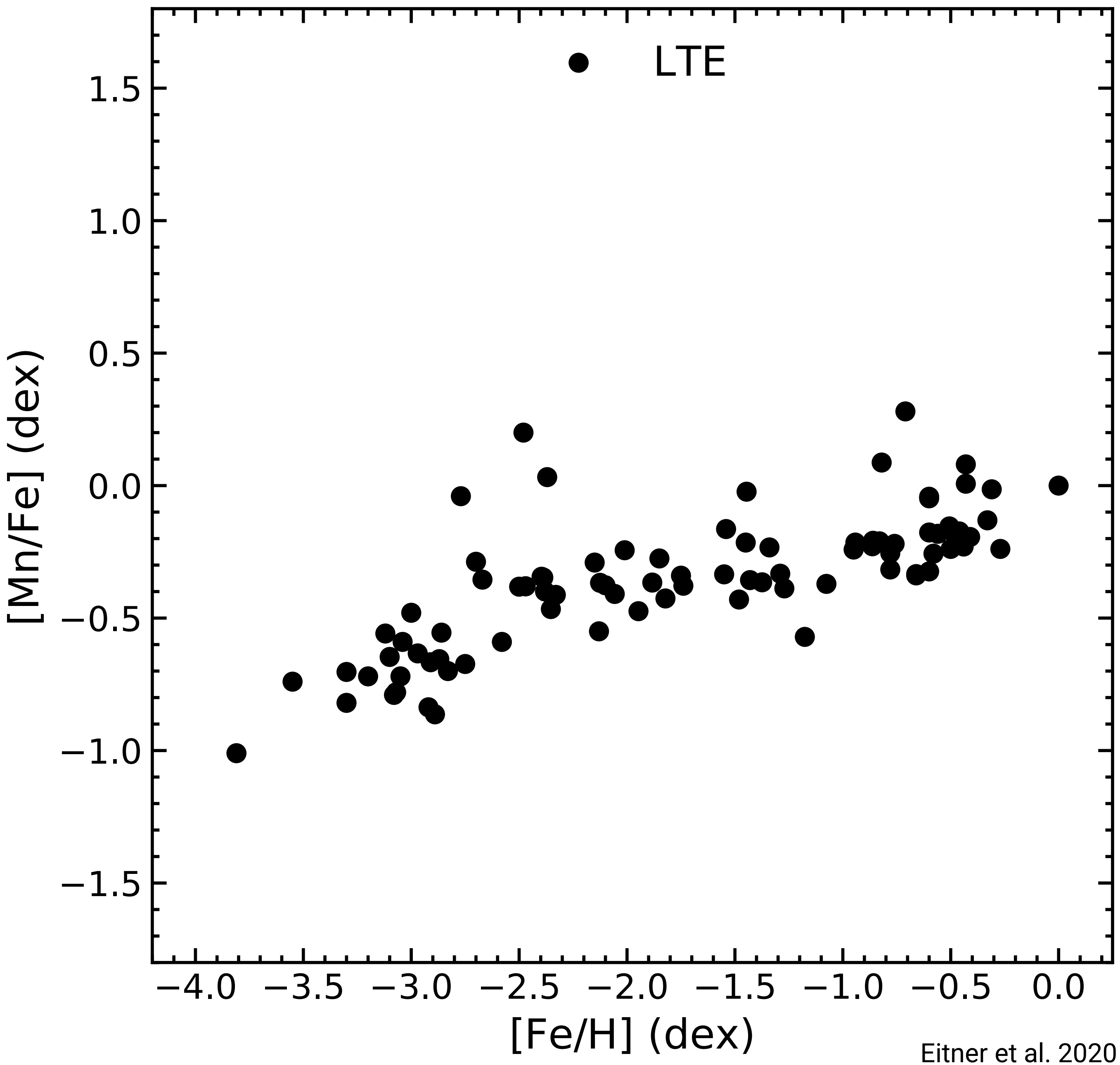
- Non-local thermal equilibrium (Non-LTE)
- No assumption of LTE in the radiative transfer
  - Energy level populations are not assumed to follow Boltzmann distribution
  - More accurate abundances?

What is NLTE?

- Non-local thermal equilibrium (Non-LTE)
- No assumption of LTE in the radiative transfer
  - Energy level populations are not assumed to follow Boltzmann distribution
  - More accurate abundances?
- Usually difficult
  - Takes longer time than LTE fitting
  - Need accurate atomic data, e.g.:
    - Energy levels
    - Bound-bound transitions, loggf
  - Quantum mechanical data
    - E.g. radiative rates for collisions w/ e-, H

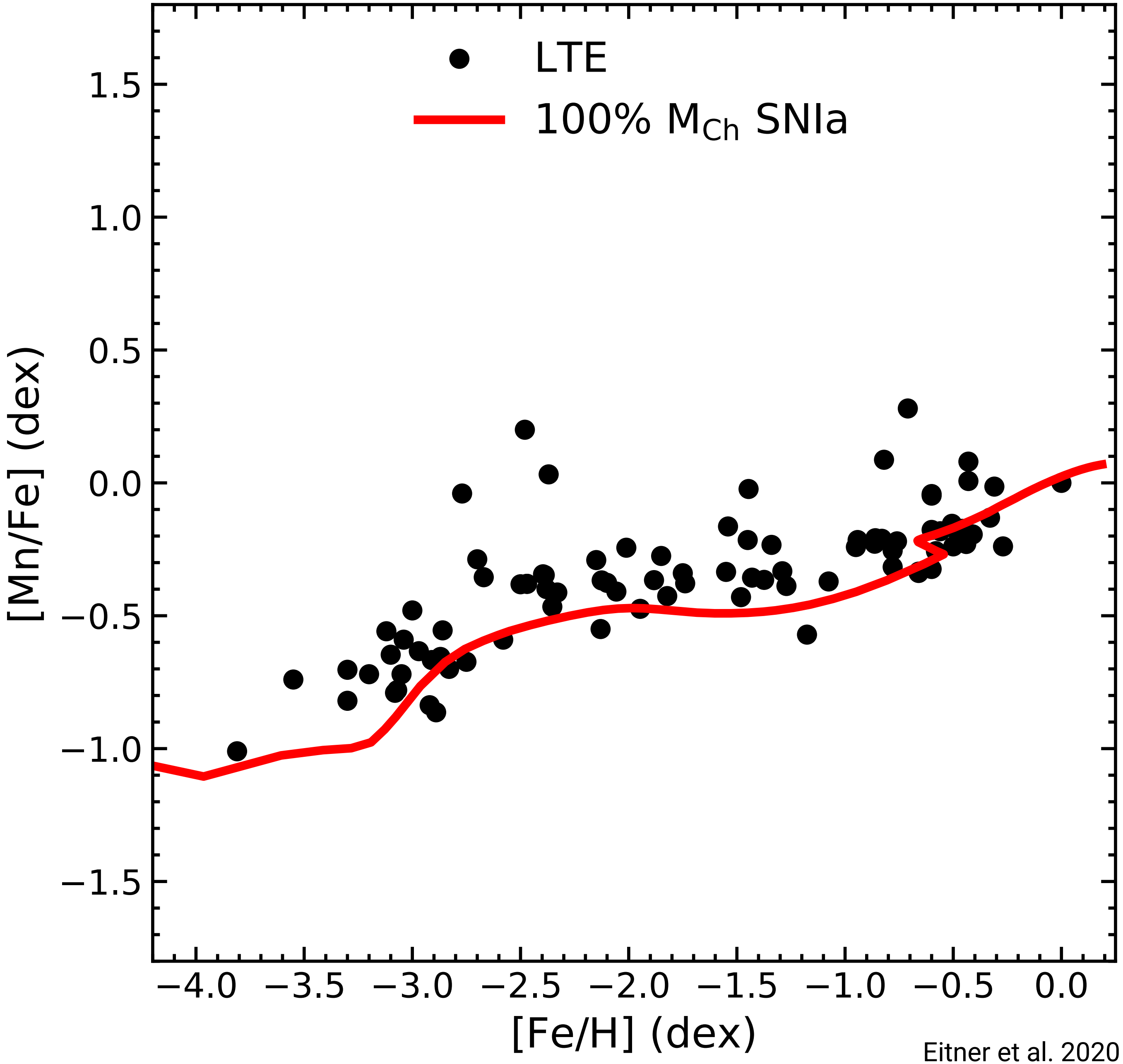
Why do NLTE?

Why do NLTE?



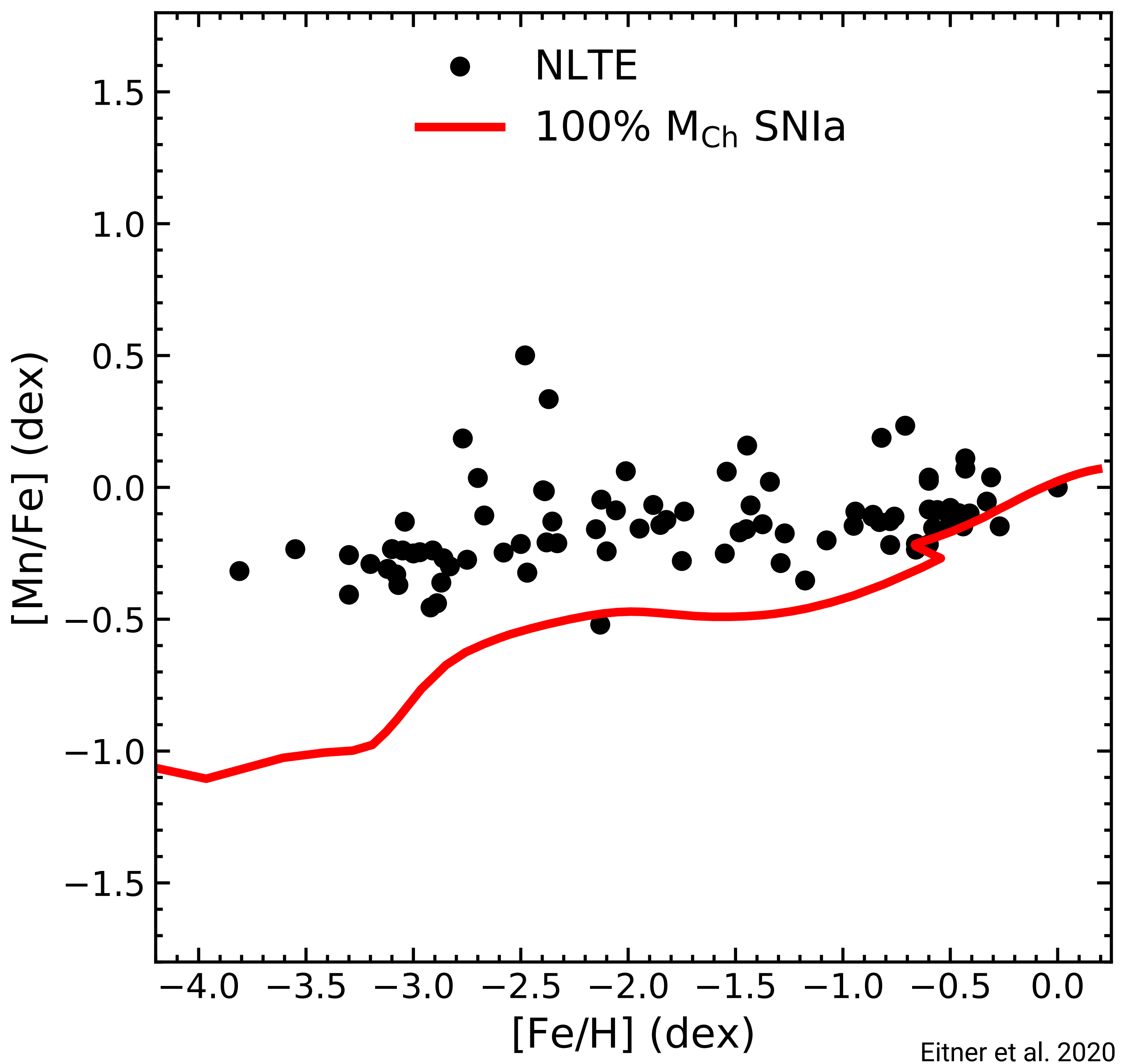
Eitner et al. 2020

Why do NLTE?



Eitner et al. 2020

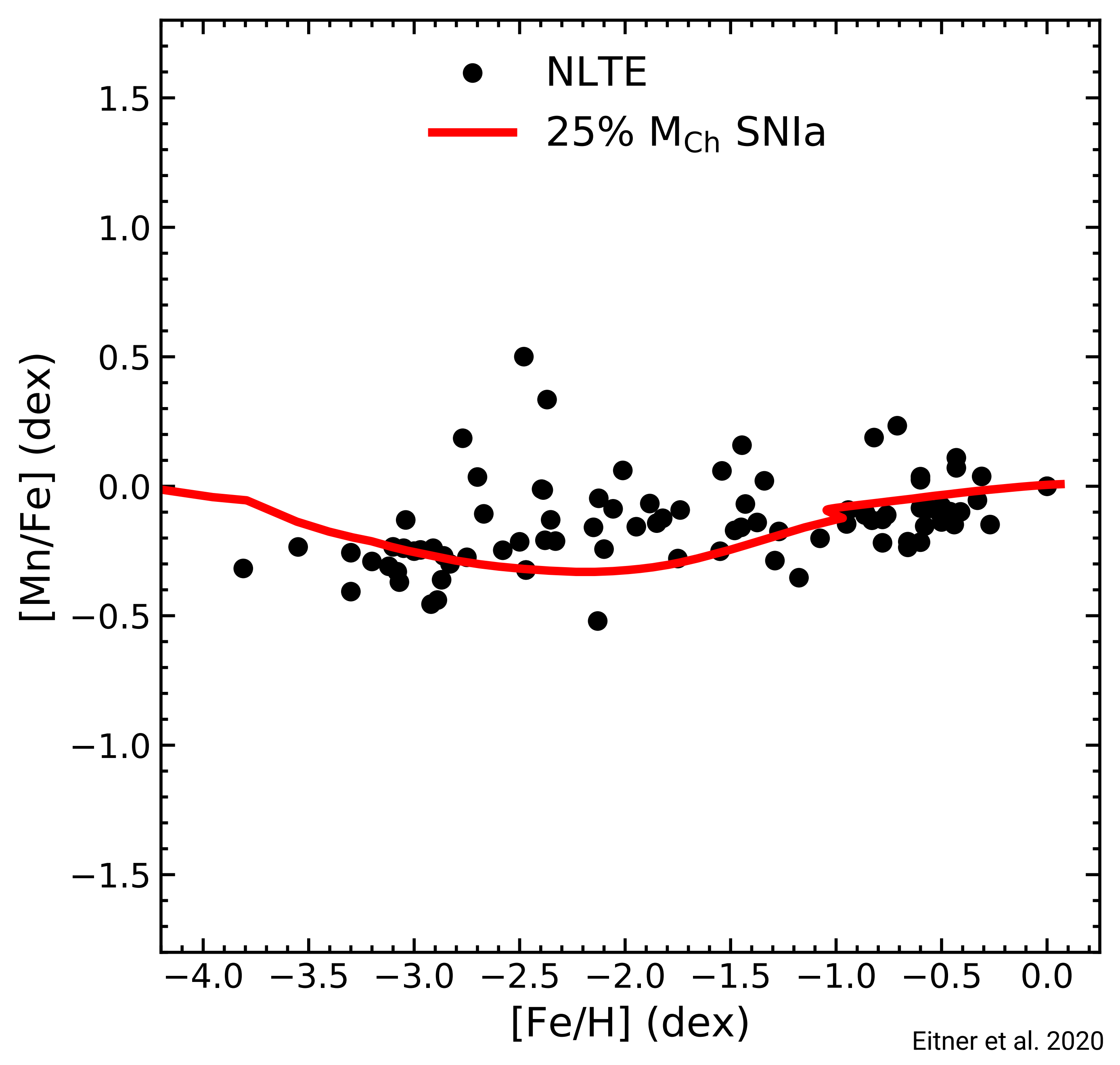
Why do NLTE?

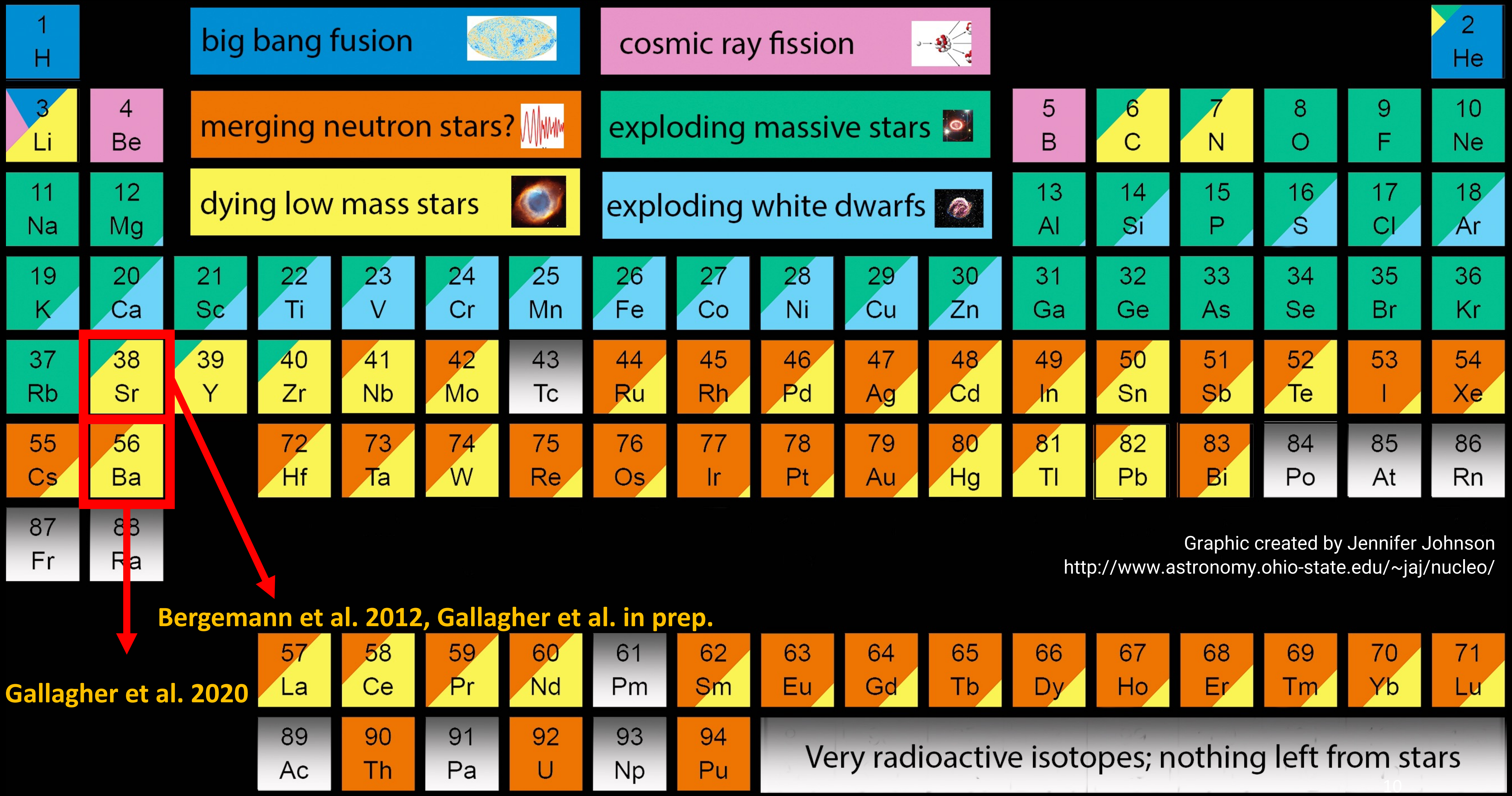


Eitner et al. 2020

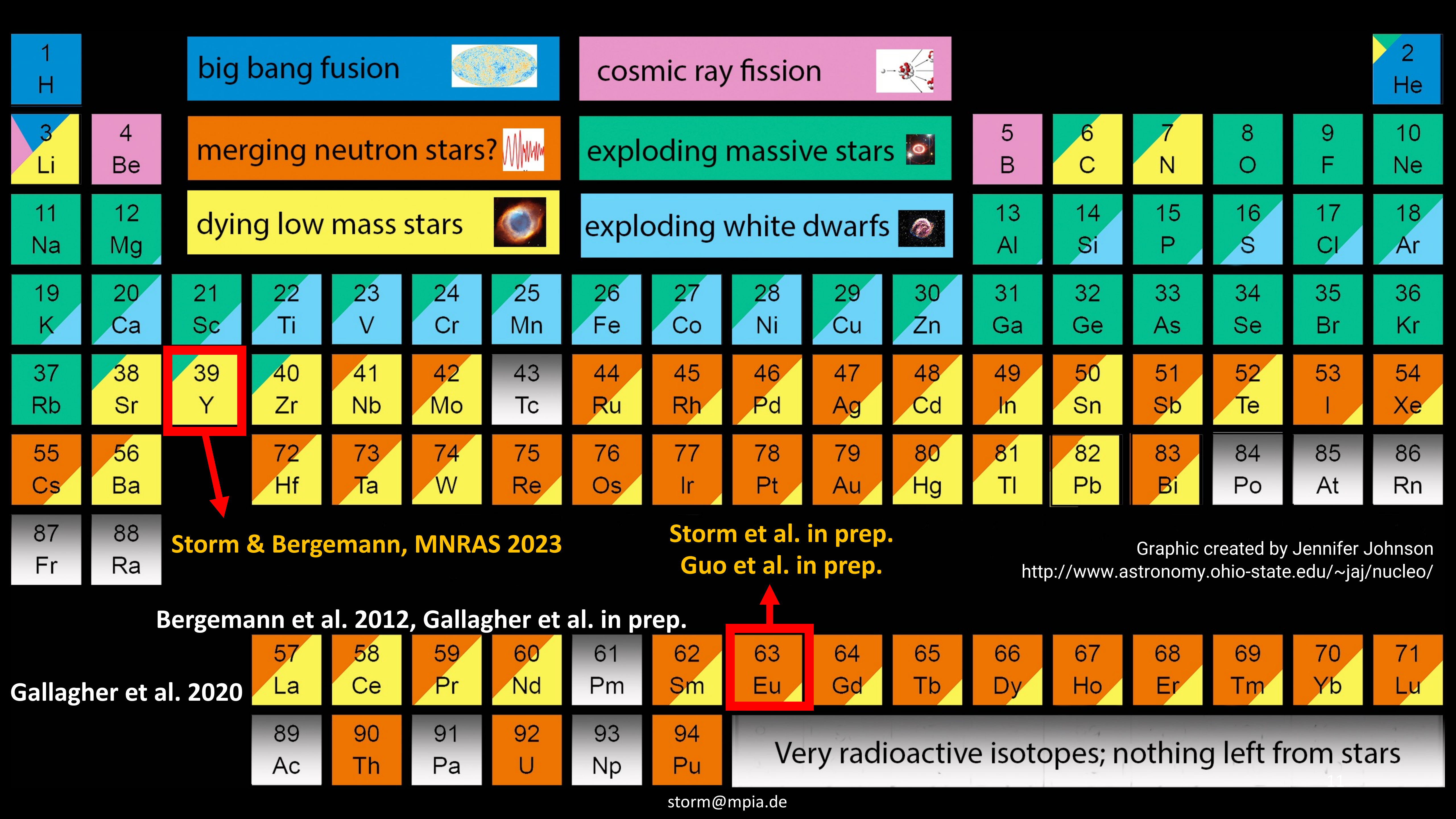
Why do NLTE?

- NLTE (and 3D) may change our understanding of the GCE models





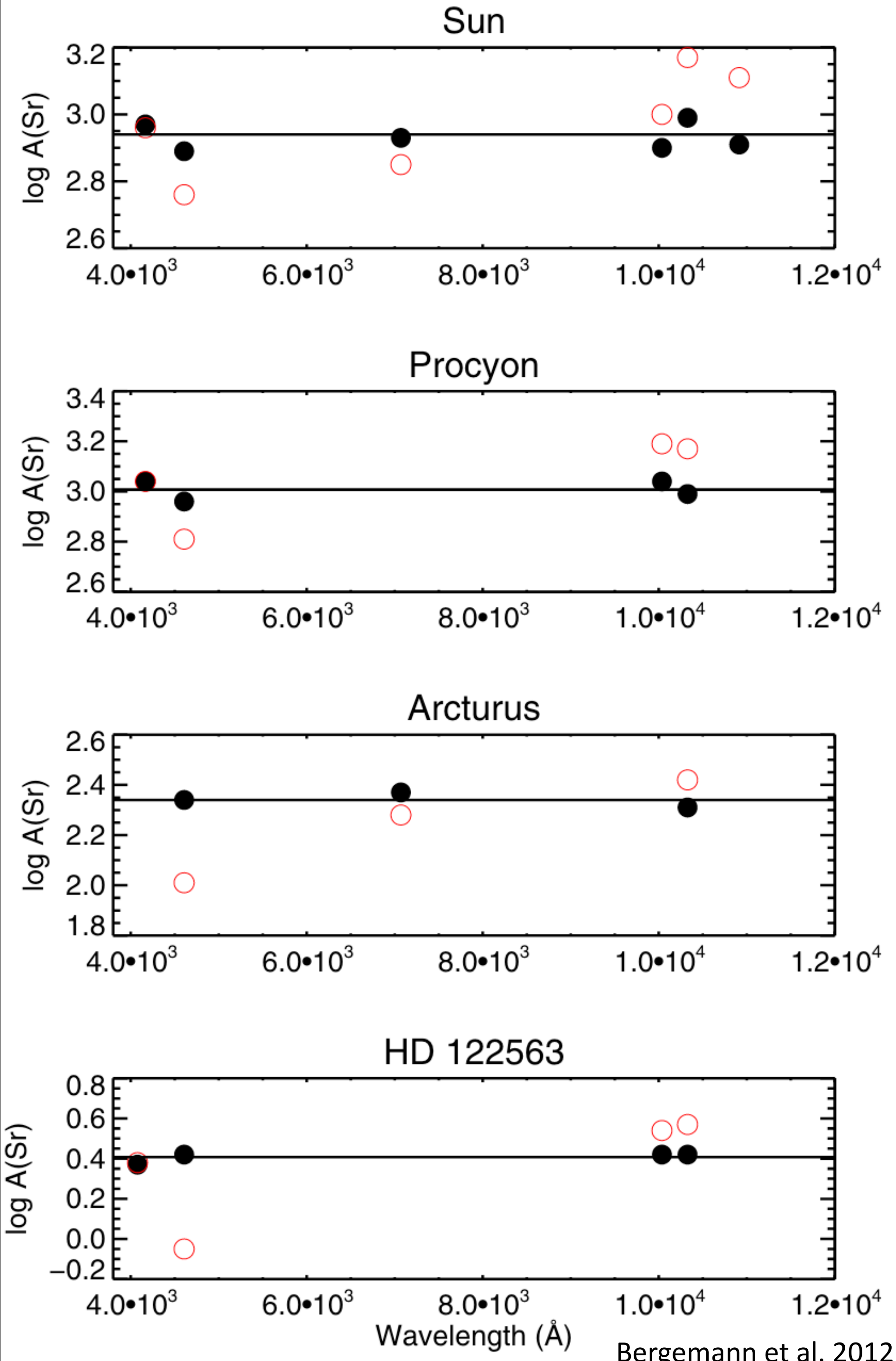
storm@mpia.de


big bang fusion
cosmic ray fission
merging neutron stars?
exploding massive stars
dying low mass stars
exploding white dwarfs
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
Storm & Bergemann, MNRAS 2023
Storm et al. in prep.
Guo et al. in prep.
Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/
Bergemann et al. 2012, Gallagher et al. in prep.
Gallagher et al. 2020
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
93 Np
94 Pu
Very radioactive isotopes; nothing left from stars
storm@mpia.de

Strontium, Barium

Strontium

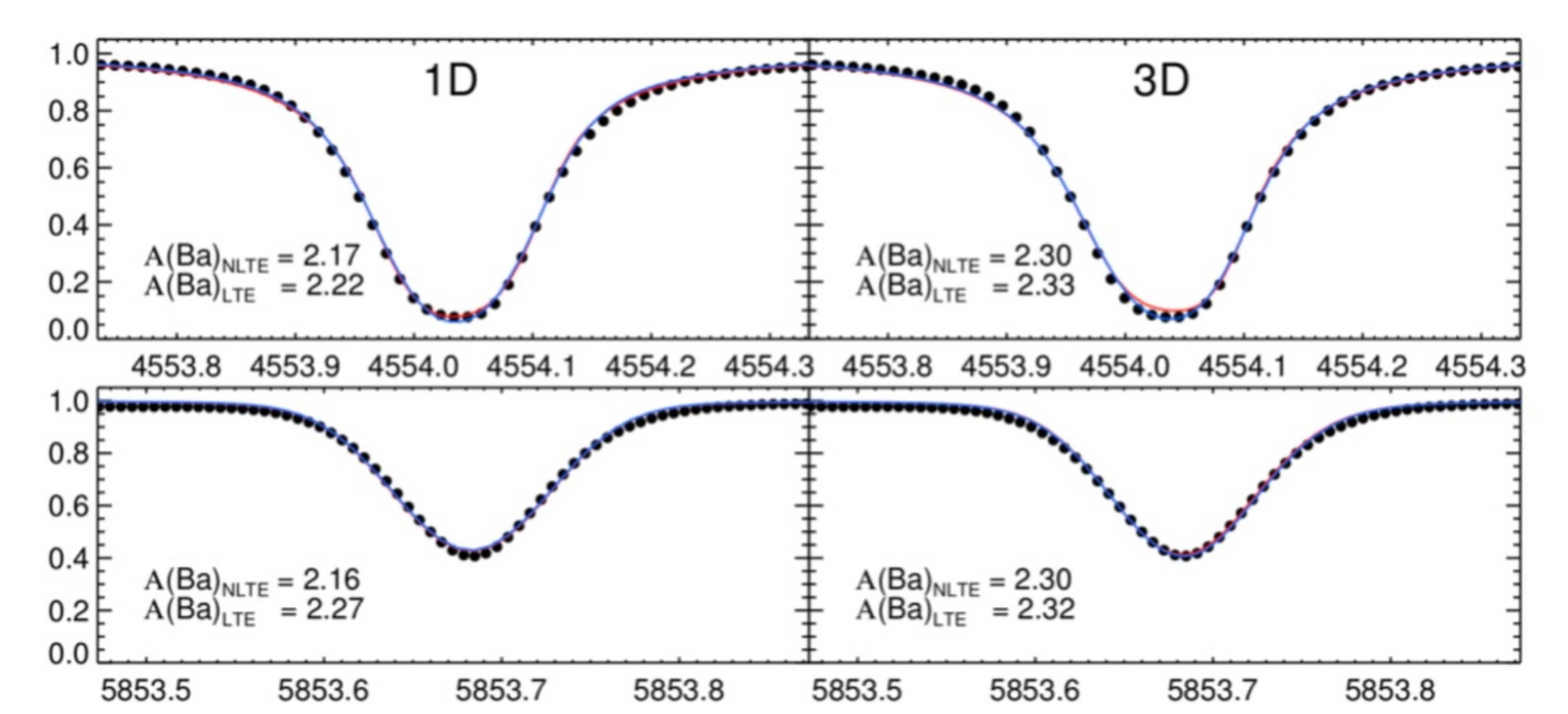
- 1st s-process peak element
- Both Sr I and Sr II
- LTE: red circle, NLTE (1D): black
- LTE: up to 0.5 dex discrepancy



Bergemann et al. 2012

Barium

- 2nd s-process peak element
- Very sensitive to physical model type
- Sun:
  - 1D NLTE A(Ba) = 2.11
  - 3D NLTE A(Ba) = 2.27

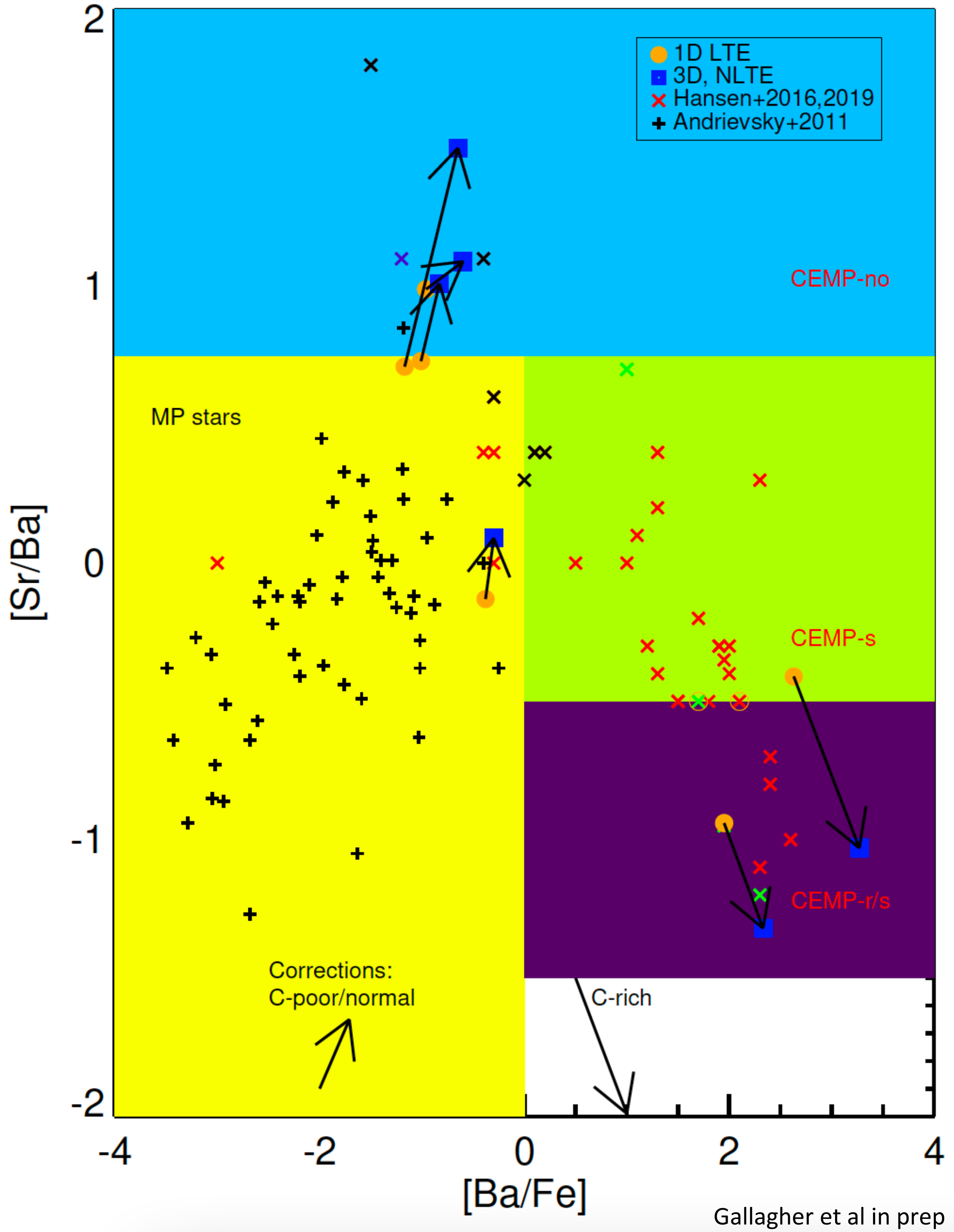


Gallagher et al. 2020

storm@mpia.de

Barium

- Classification of the CEMP stars: may change with NLTE effects

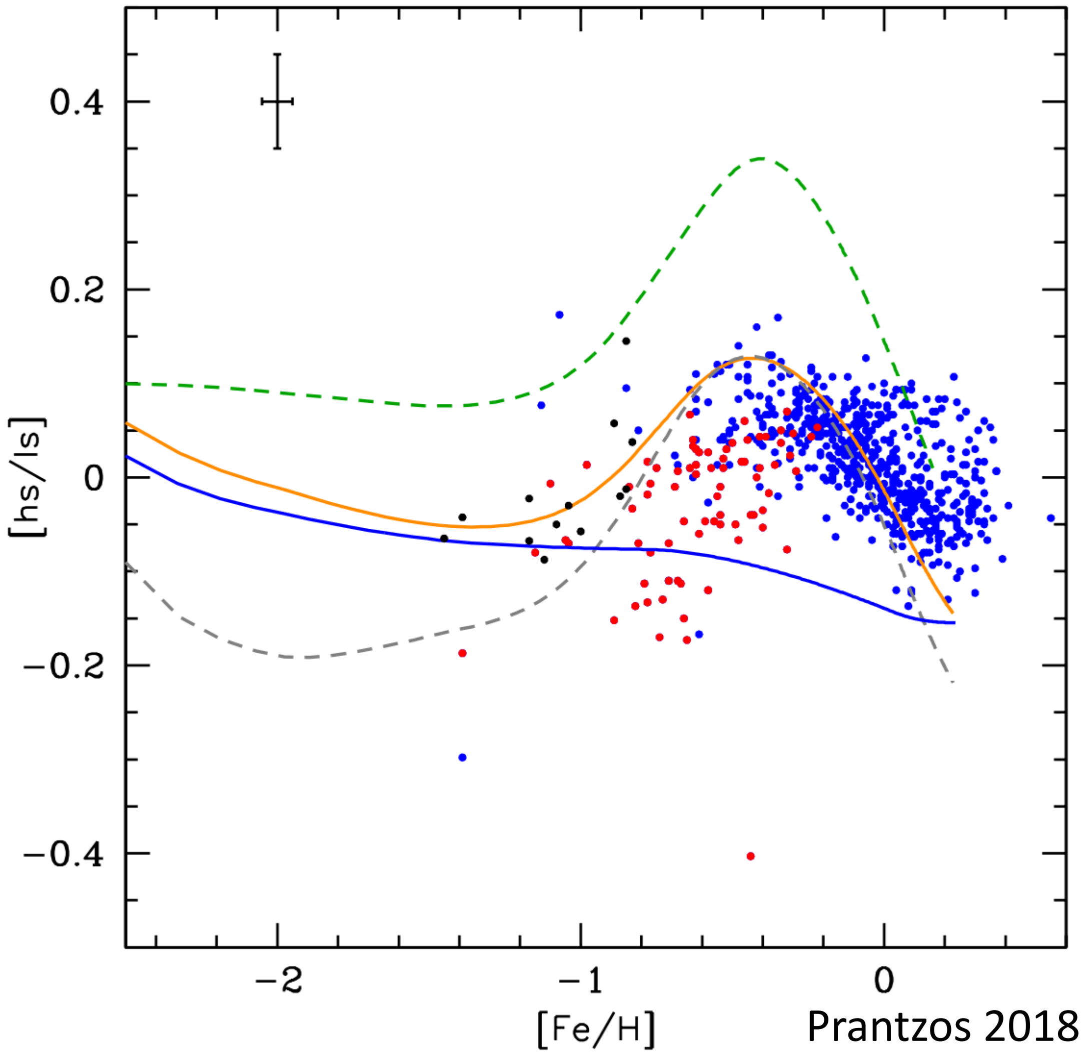


Gallagher et al in prep

Yttrium (1D)

Yttrium

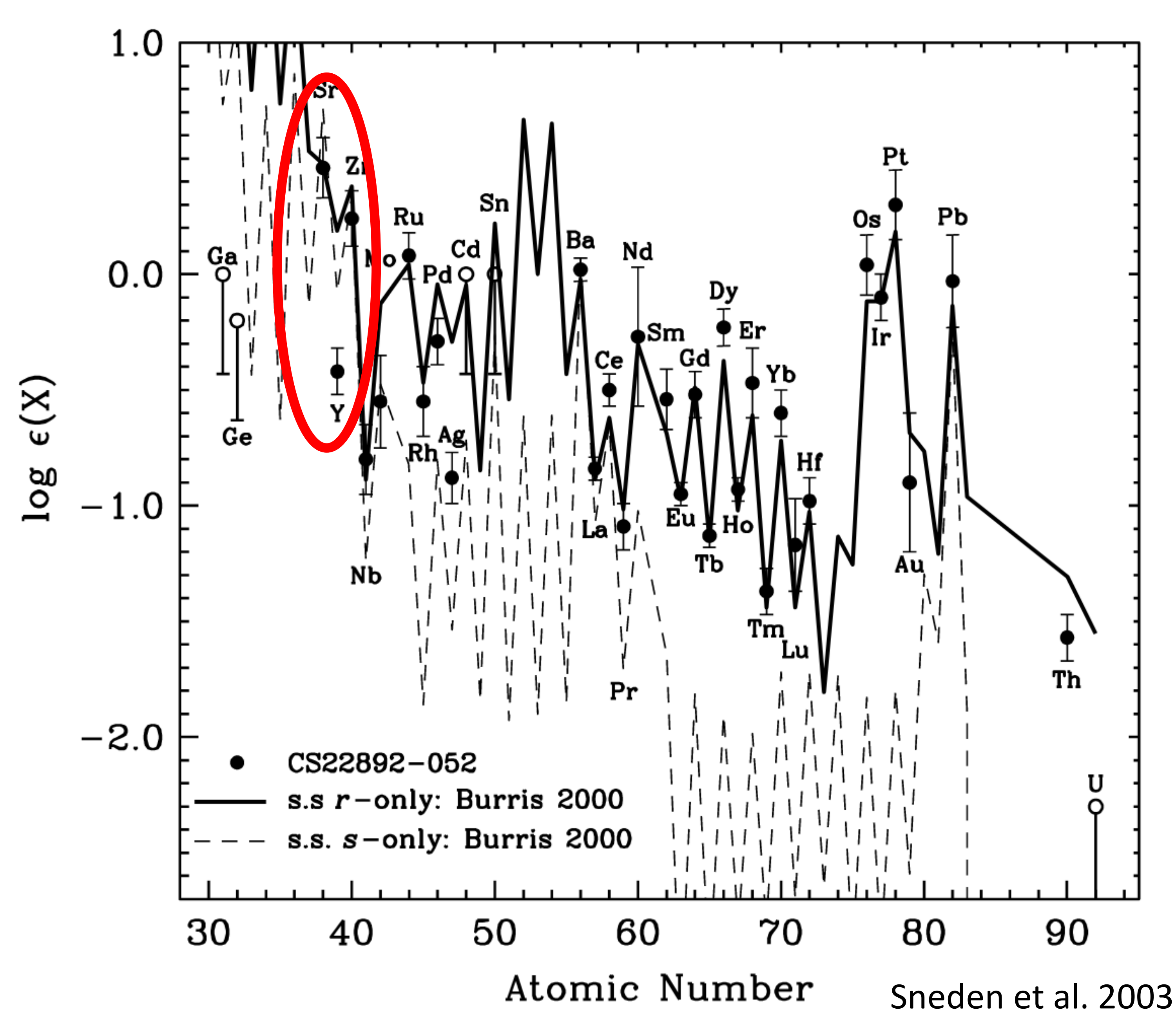
- 1st s-process peak element
- Used in:
  - [Ba/Y]: s-process efficiency (Travaglio 2004, Prantzos 2018)
  - [Y/Mg]: chemical clock for solar like stars (e.g. da Silva et al. 2012, Nissen 2015)



Prantzos 2018

Previous studies

- Y underabundant compared to Sr and Zr?
  - e.g. Sneden et al. 2003
  - CS 22892-052: 0.15-0.30 dex lower than Sr and Zr

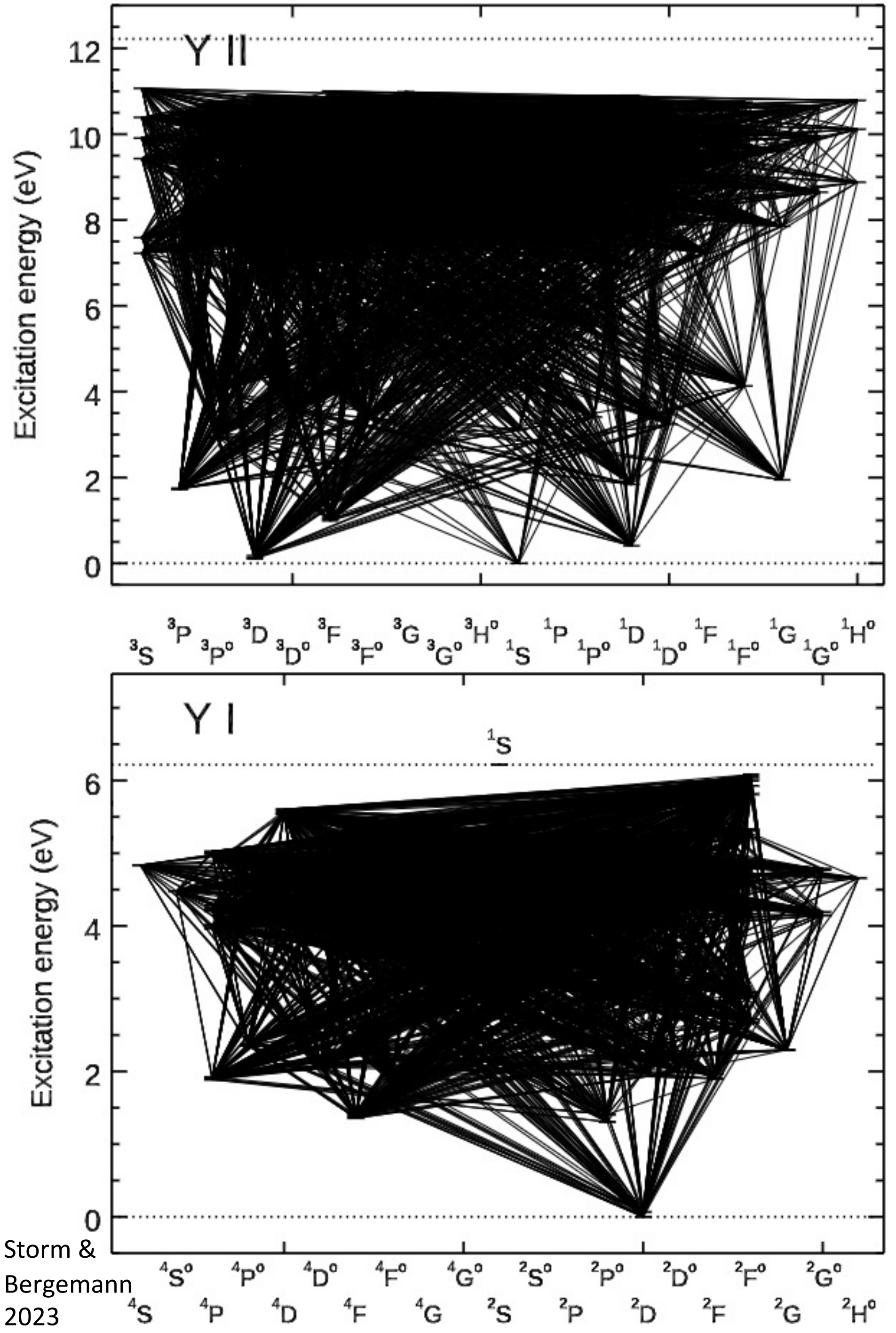


Sneden et al. 2003

storm@mpia.de

Y model atom

- 423 Y I and Y II levels
- Collisional data with e- and H: classical recipes
- NLTE calculations:
  - MULTI1D
    - Departure coefficients for TurboSpectrum (Plez et al. 2012, Gerber et al. 2023) -> can fit with TSFitPy + TurboSpectrum
      - https://github.com/TSFitPy-developers/TSFitPy
      - 15 elements in NLTE for 1D or ”average 3D”
  - MULTI3D@DISPATCH (Eitner et al. in prep)

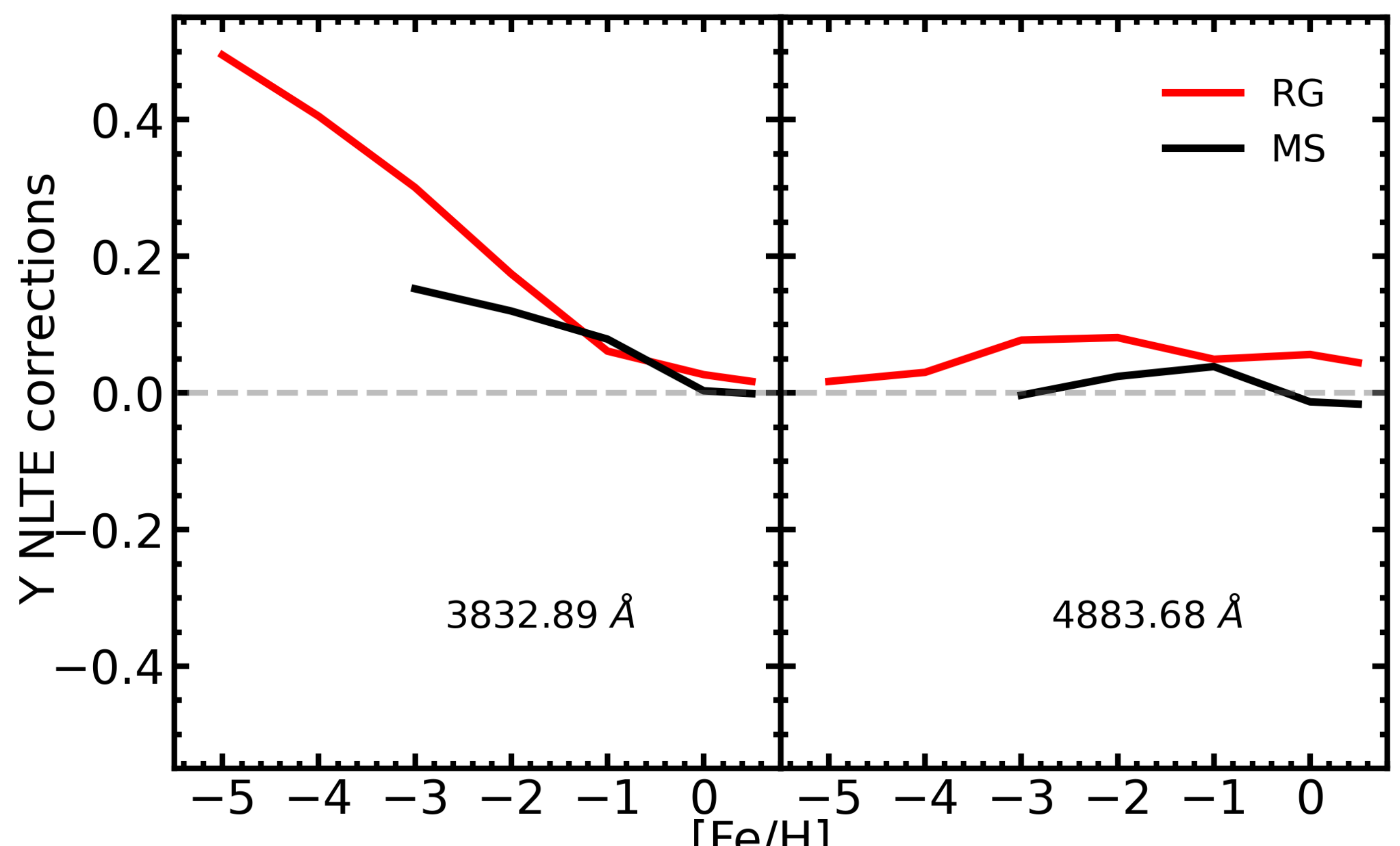


Storm & Bergemann 2023

storm@mpia.de

Yttrium NLTE corrections

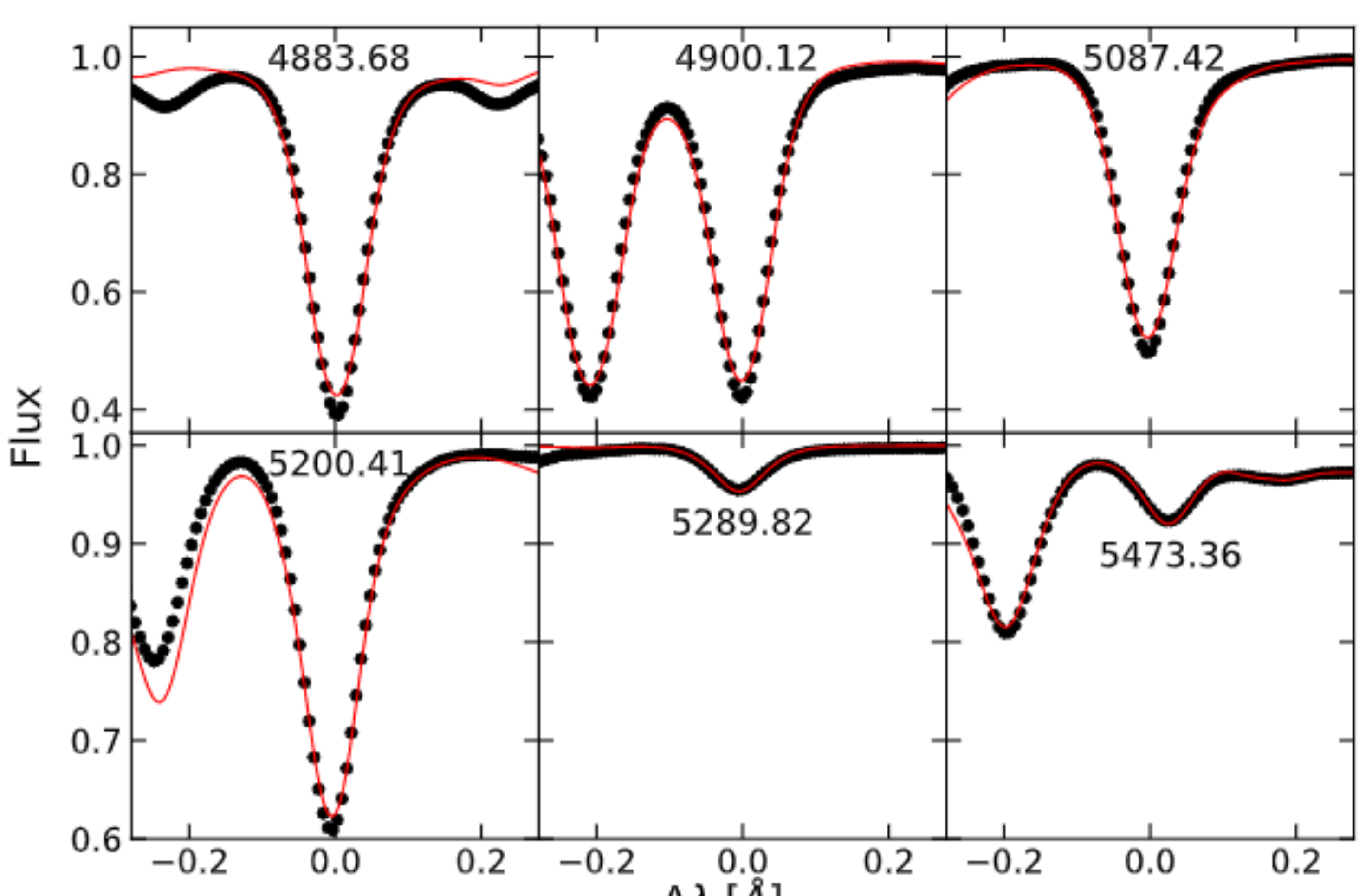
- Higher for red giants



Adapted from Storm & Bergemann 2023

The Sun

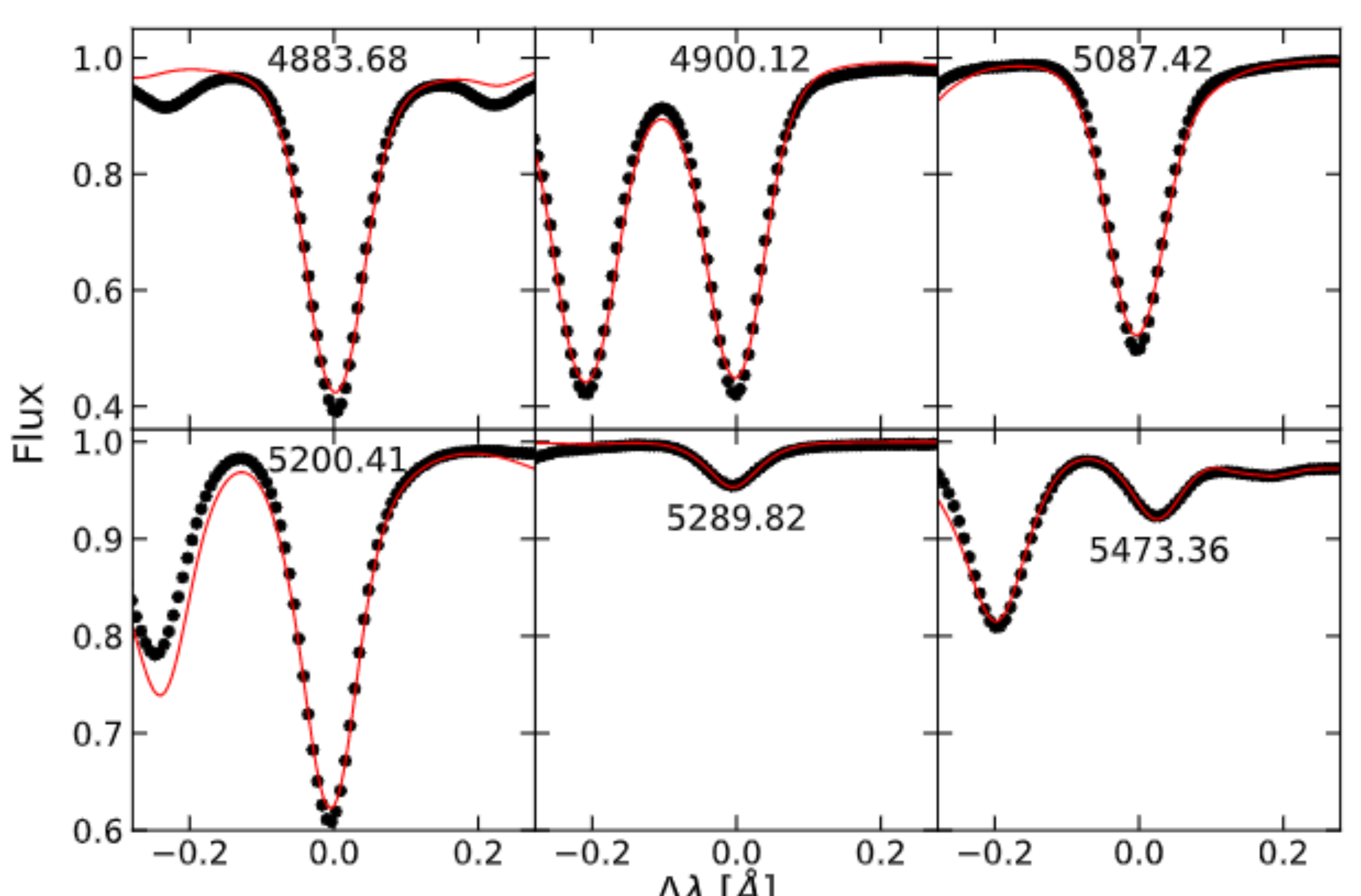
- Grevesse et al. 2015:
    - Older loggf values
    - 1D LTE: 2.14 ± 0.06
    - 3D LTE: 2.21 ± 0.05



Storm & Bergemann 2023

The Sun

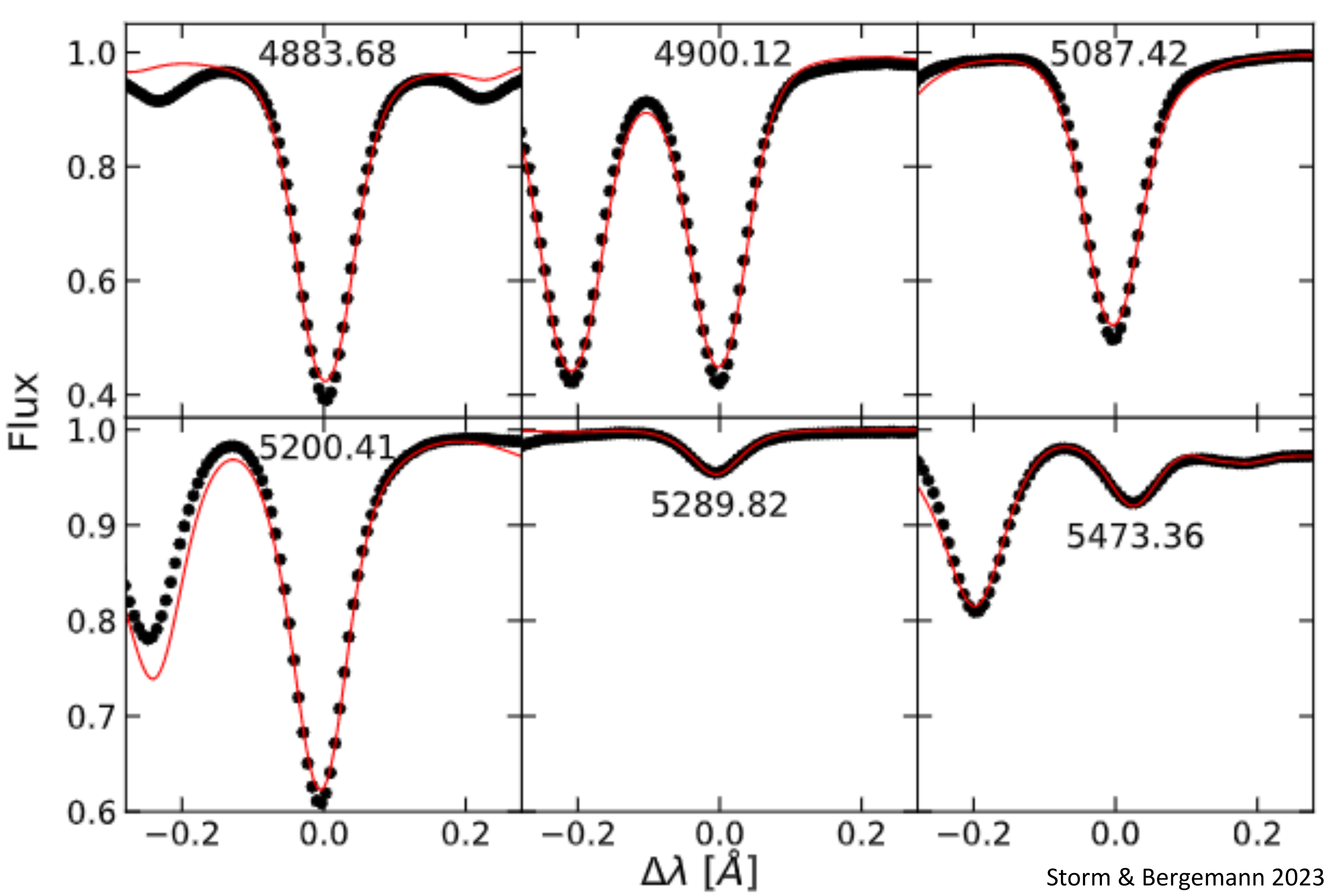
- Grevesse et al. 2015:
  - Older loggf values
  - 1D LTE: 2.14 ± 0.06
  - 3D LTE: 2.21 ± 0.05
- Meteoric value (Lodders et al. 2009):
  - 2.17 ± 0.04



Storm & Bergemann 2023

The Sun

- Grevesse et al. 2015:
  - Older loggf values
  - 1D LTE: 2.14 ± 0.06
  - 3D LTE: 2.21 ± 0.05
- Meteoric value (Lodders et al. 2009):
  - 2.17 ± 0.04
- Our A(Y)
  - 1D LTE: 2.08 ± 0.04
  - 1D NLTE: 2.12 ± 0.04
  - 3D NLTE: Next slides



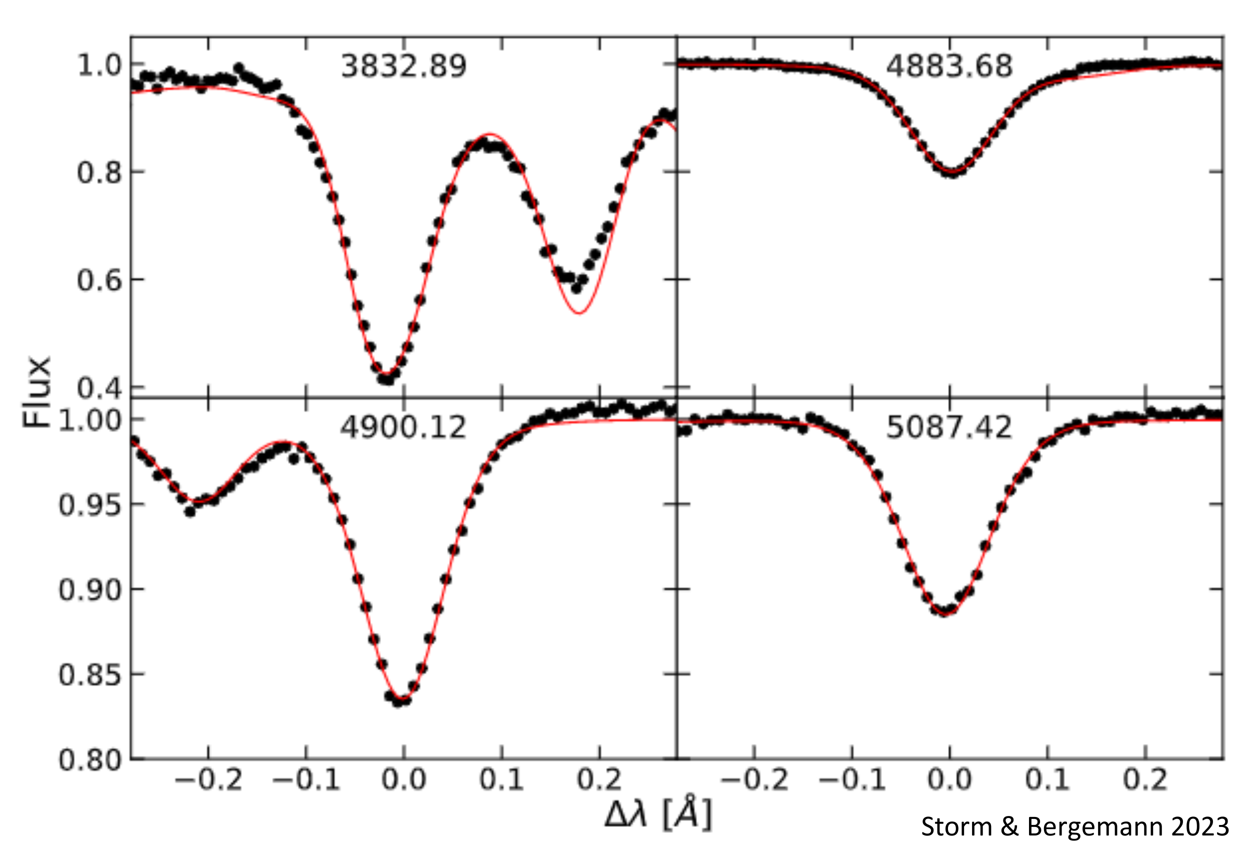
Storm & Bergemann 2023

Fitting benchmark HD122563 (1D)

Yttrium

HD 122563

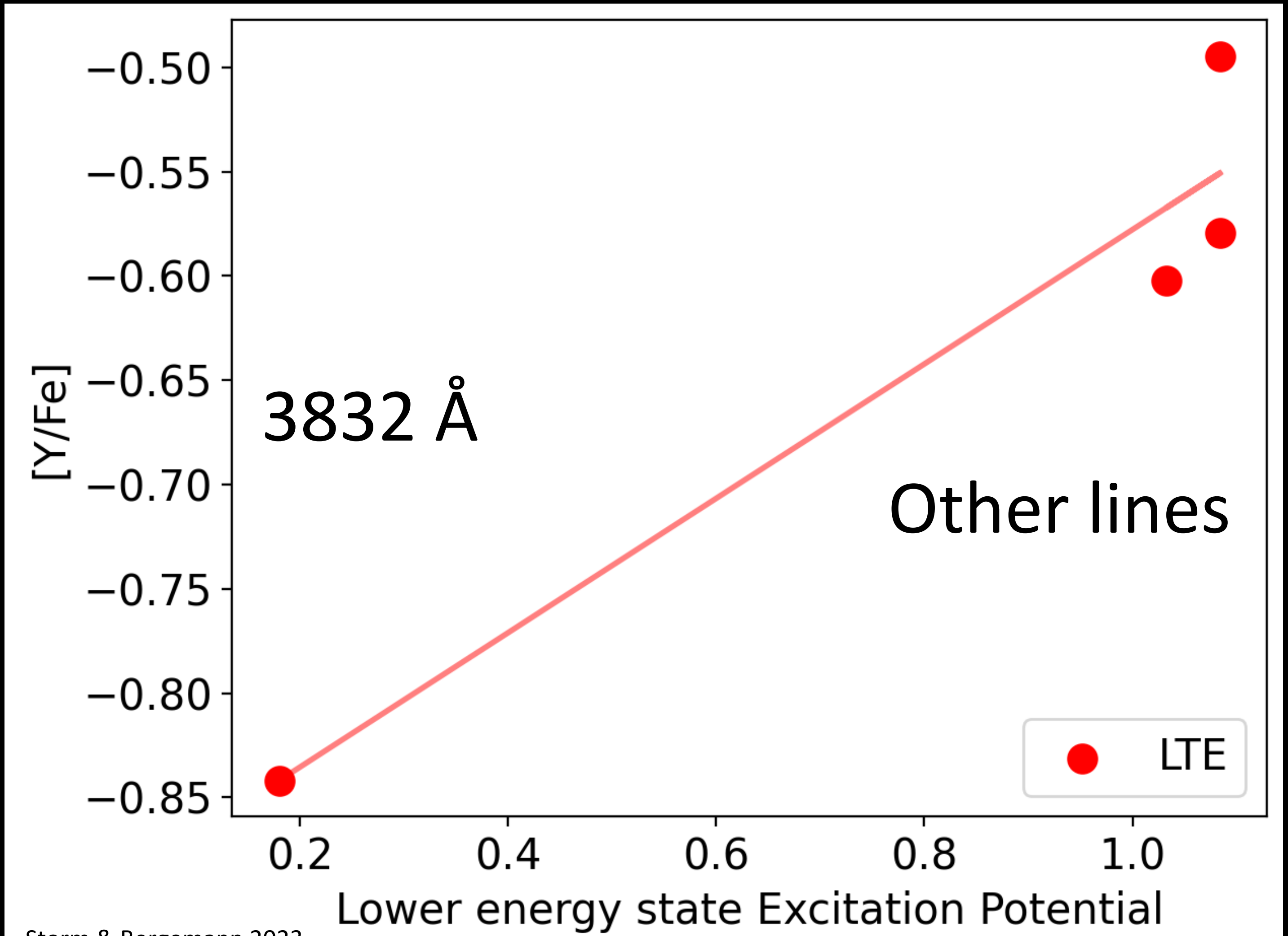
- Well known Gaia/4MOST benchmark star
- Teff = 4600, logg=1.4, [Fe/H] = -2.6
- Previous studies:
    - Aoki 2005: A(Y) = -0.84 ± 0.24
    - Honda 2006: A(Y) = -0.93 ± 0.09



Storm & Bergemann 2023

HD 122563

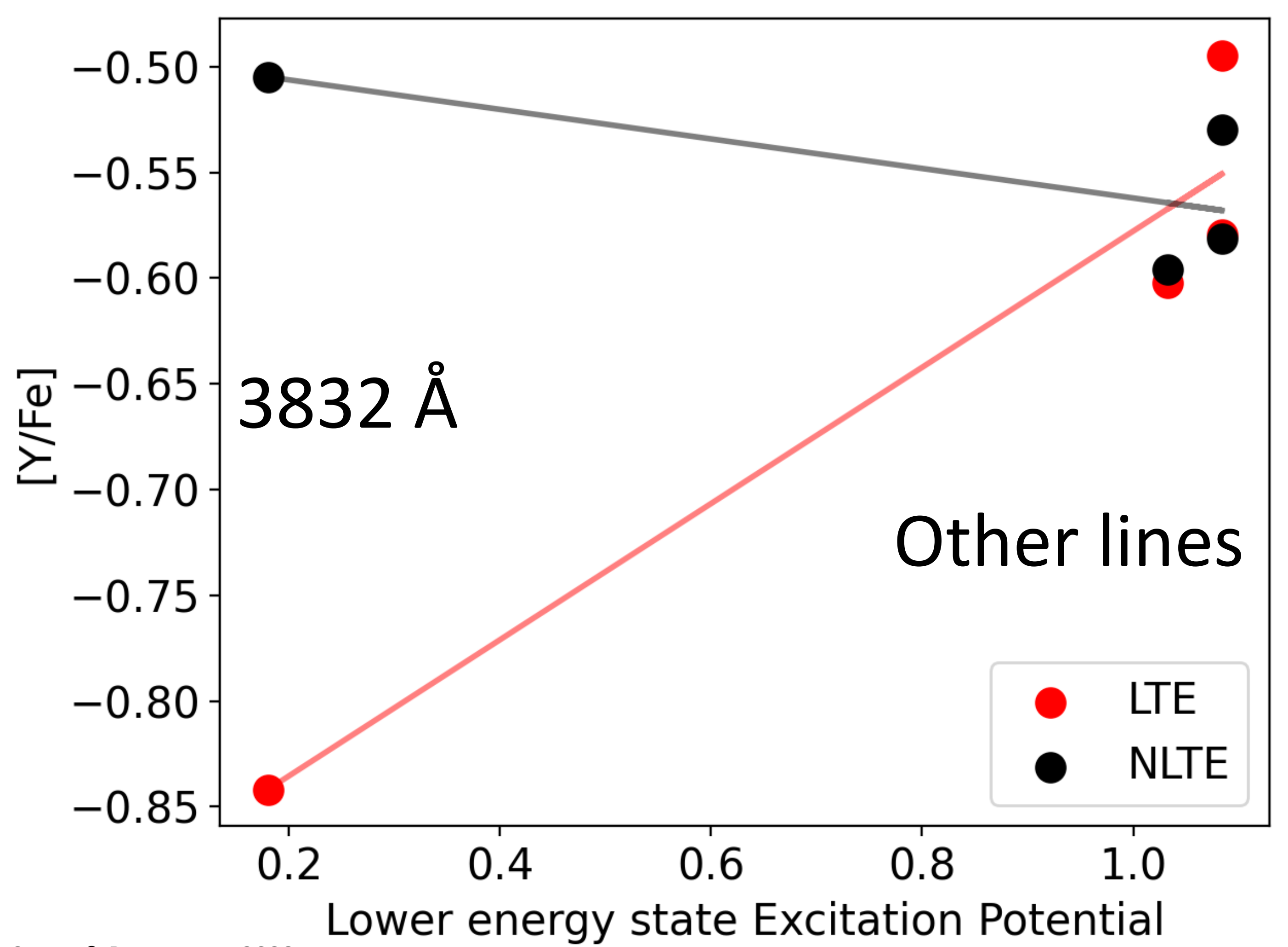
- Our results A(Y):
  - 1D LTE: -1.02 ± 0.13



Storm & Bergemann 2023

HD 122563

- Our results A(Y):
  - 1D LTE: -1.02 ± 0.13
  - 1D NLTE: -0.89 ± 0.04
    - Full agreement with previous studies, but lower spread

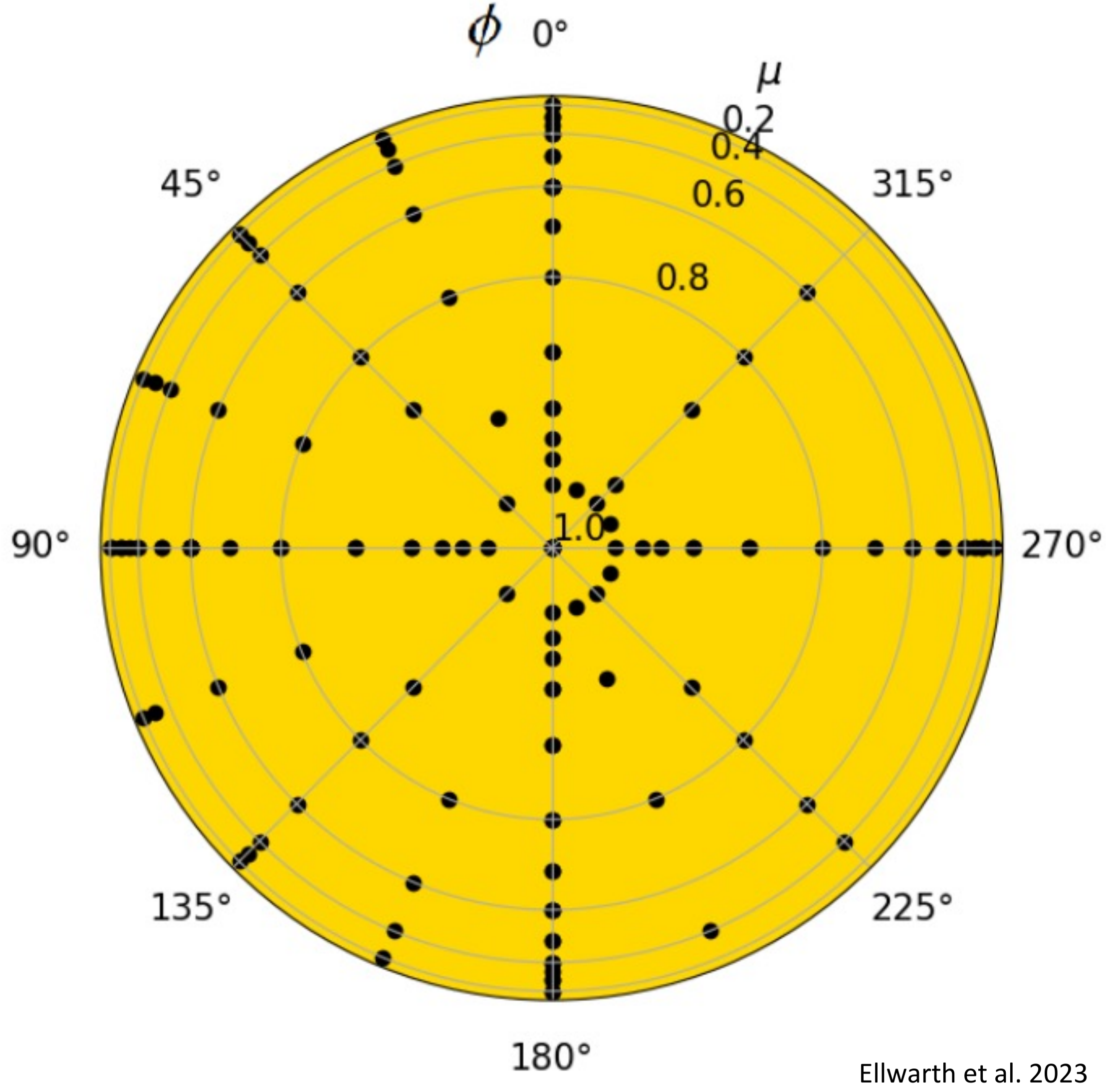


Storm & Bergemann 2023

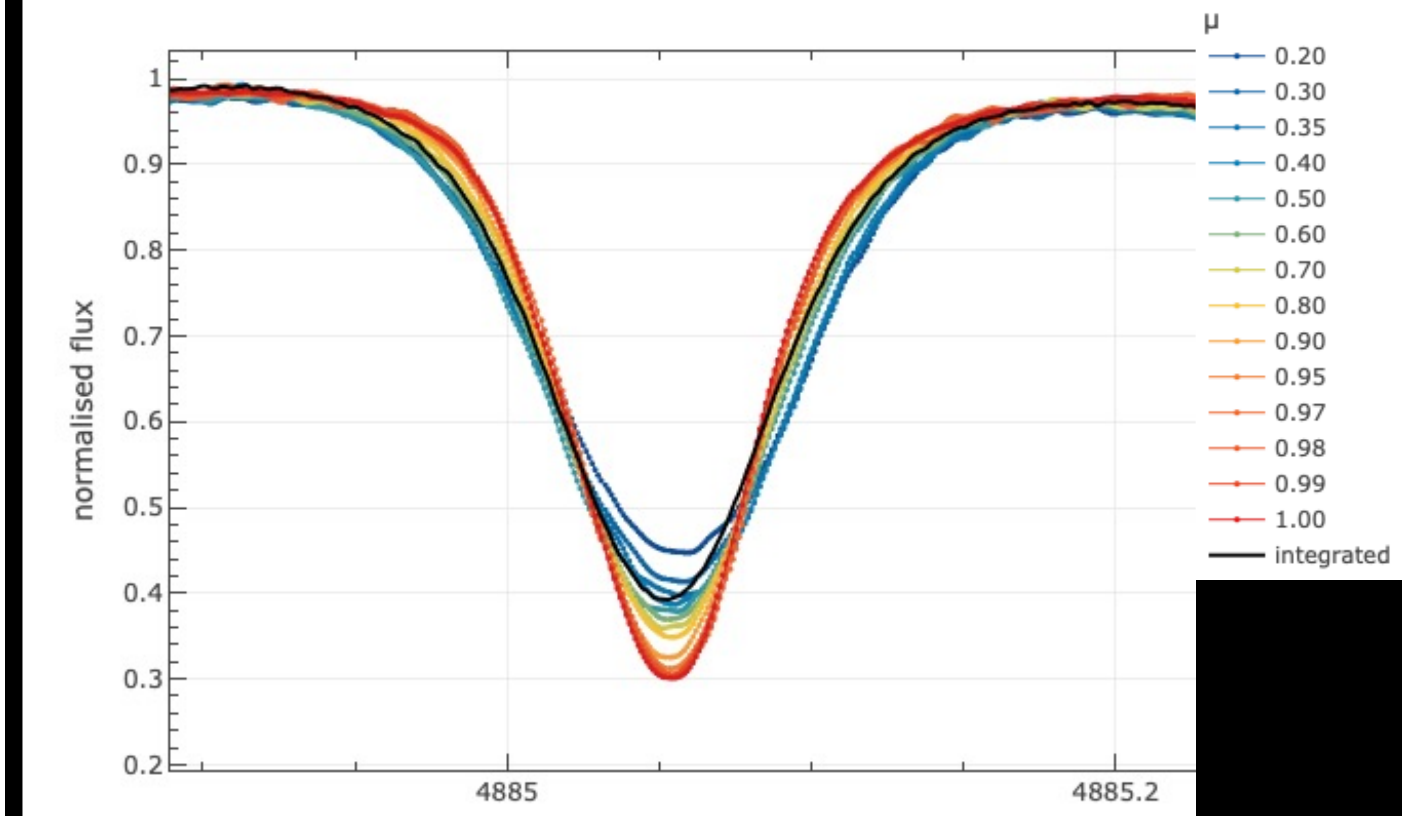
Centre-to-limb variation (3D)

Yttrium

Centre-to-limb variation (CLV)



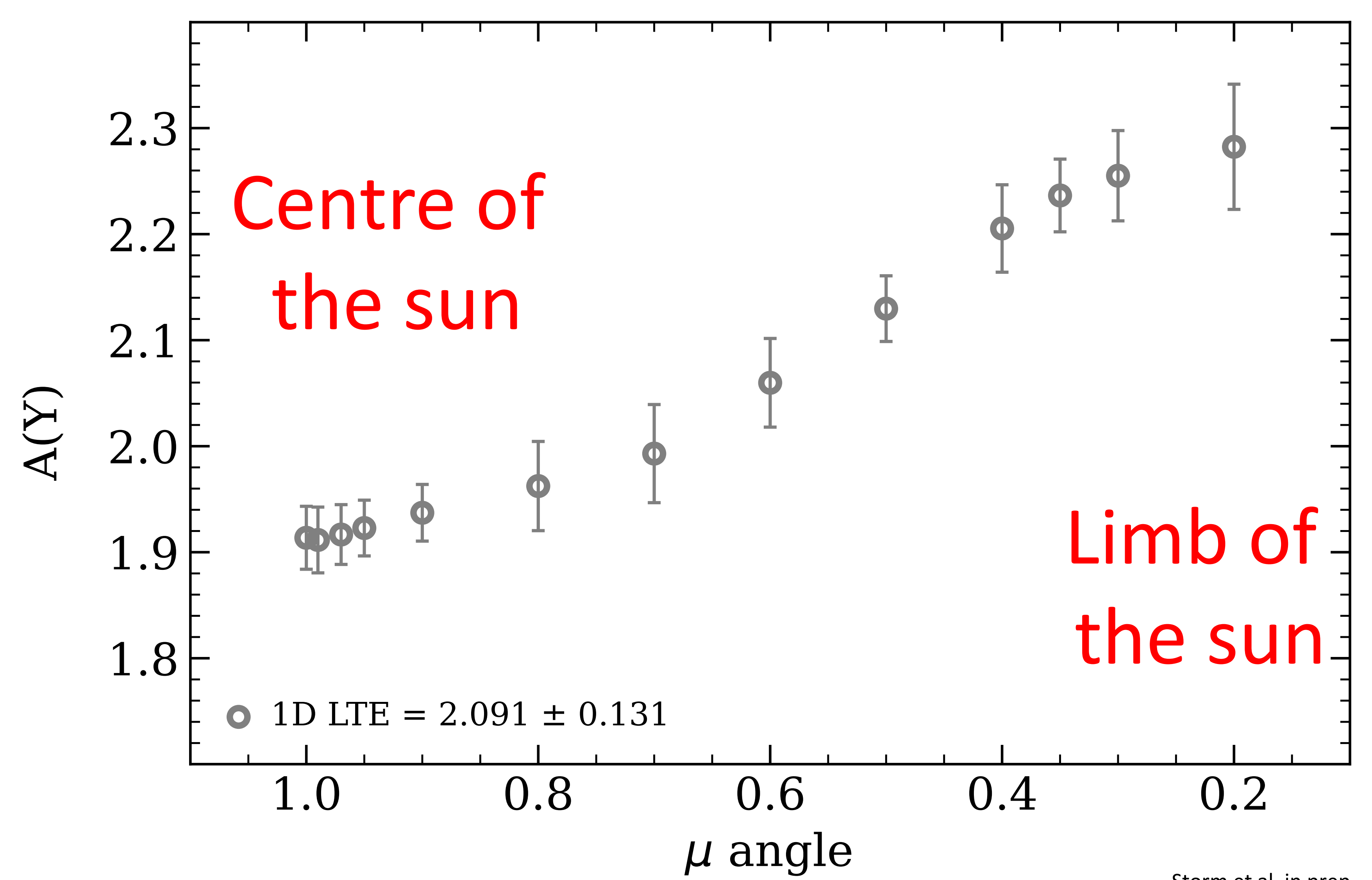
Ellwarth et al. 2023



IAG solar spatial resolved spectrum library

CLV

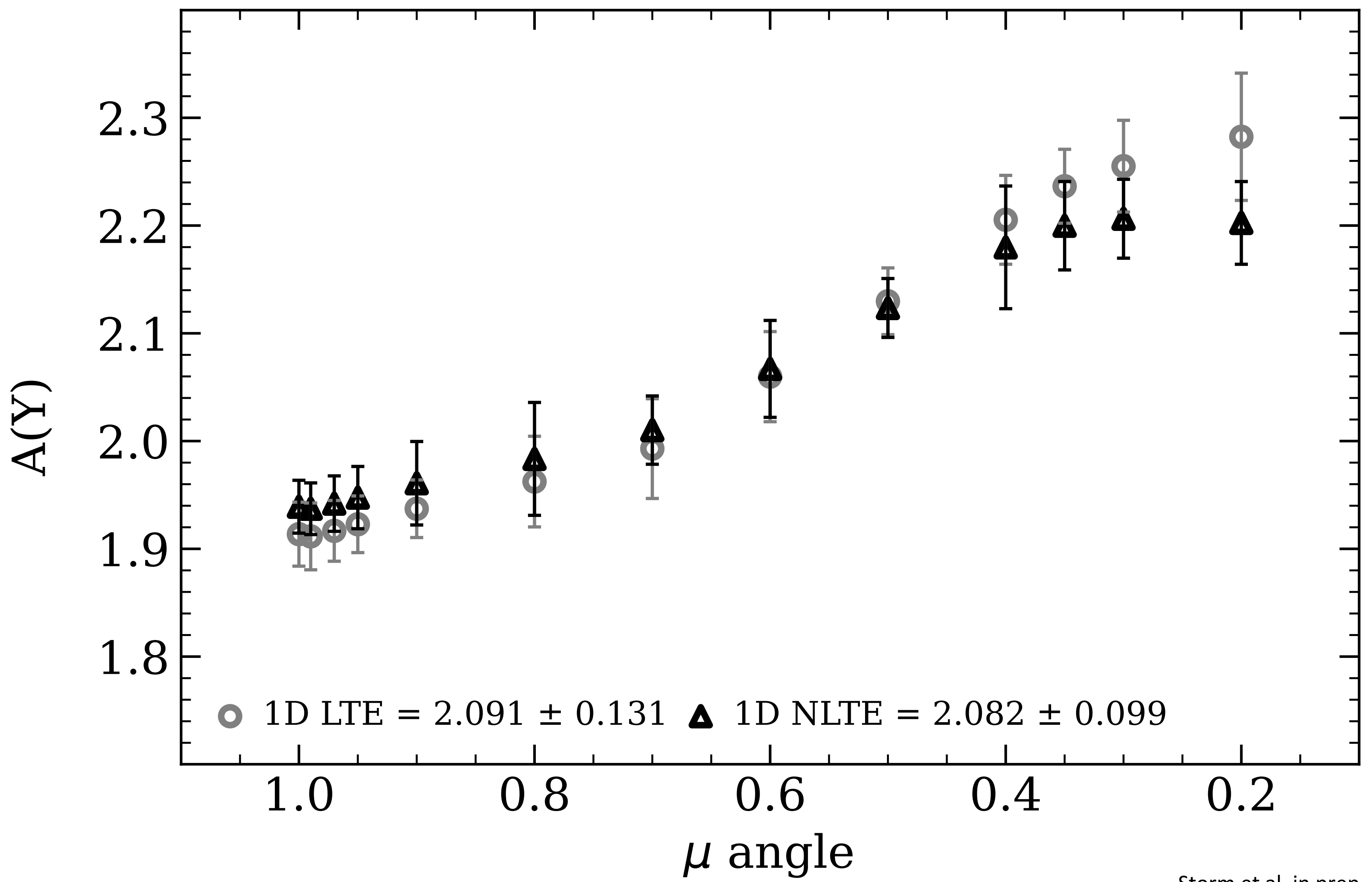
- Solar centre-to-limb variation
- Updated model atom
  - With Y+H quantum-mechanial rates (from Wang et al. 2023, subm.)



Storm et al. in prep.

CLV

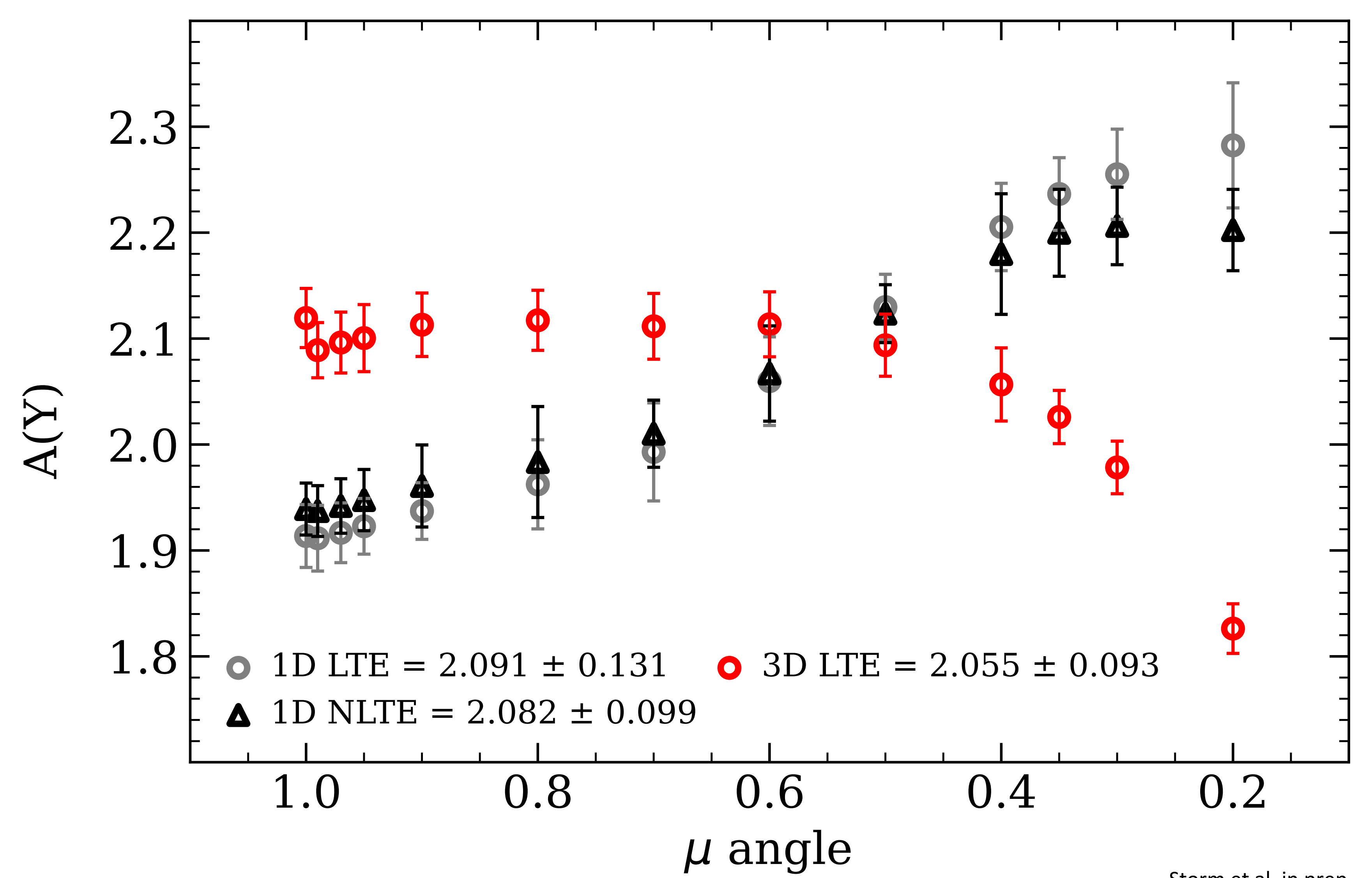
- Solar centre-to-limb variation



Storm et al. in prep.

CLV

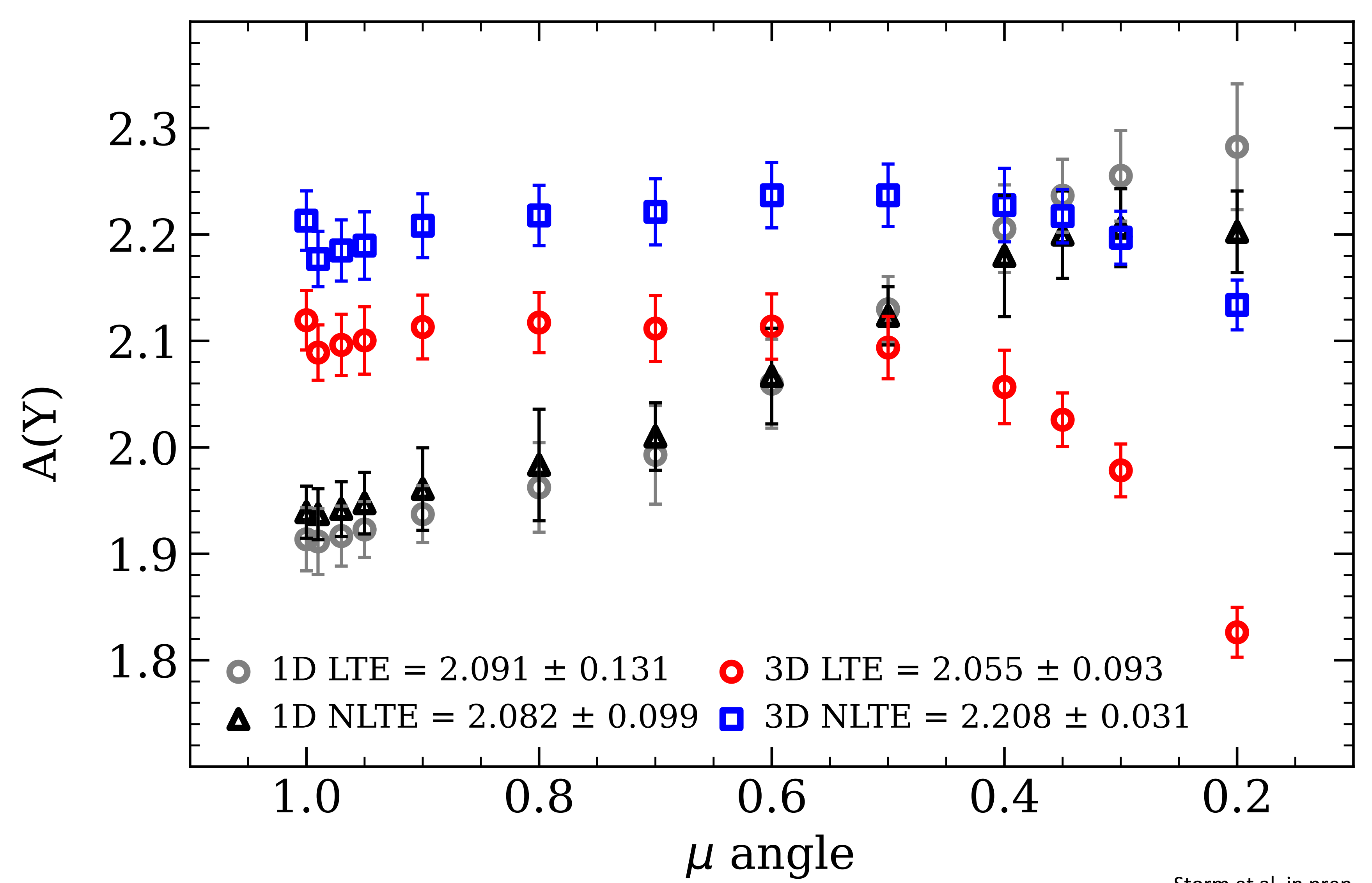
- Solar centre-to-limb variation



Storm et al. in prep.

CLV

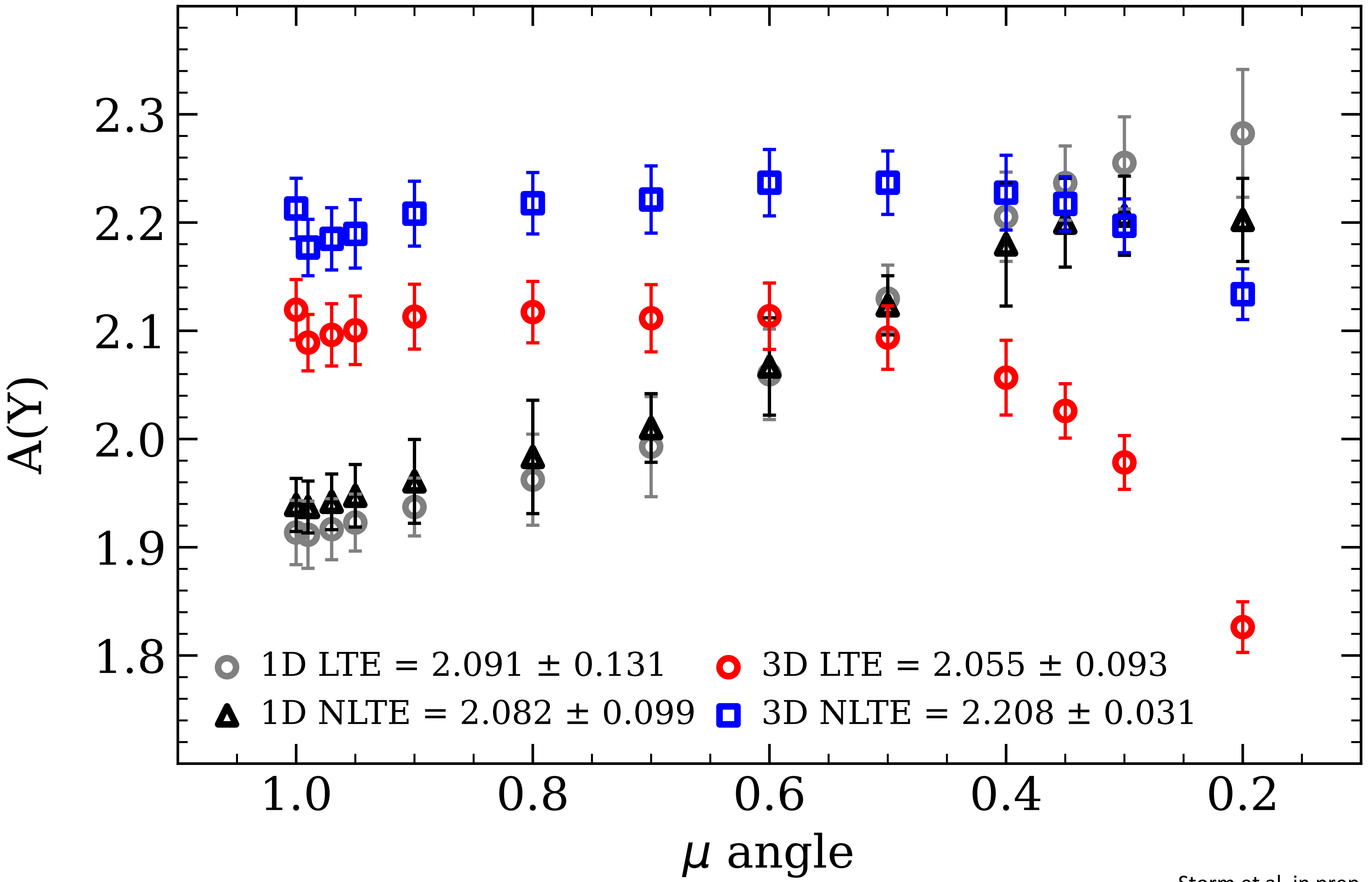
- Solar centre-to-limb variation



Storm et al. in prep.

CLV

- Repeat for other lines:
  - 4883
  - 4900
  - 5087
- Our rederived solar **3D NLTE**:
  - A(Y) = 2.20 ± 0.04
    - ± 0.07 systematic
  - But! Depends on loggf choice
    - Need very accurate loggf values!!

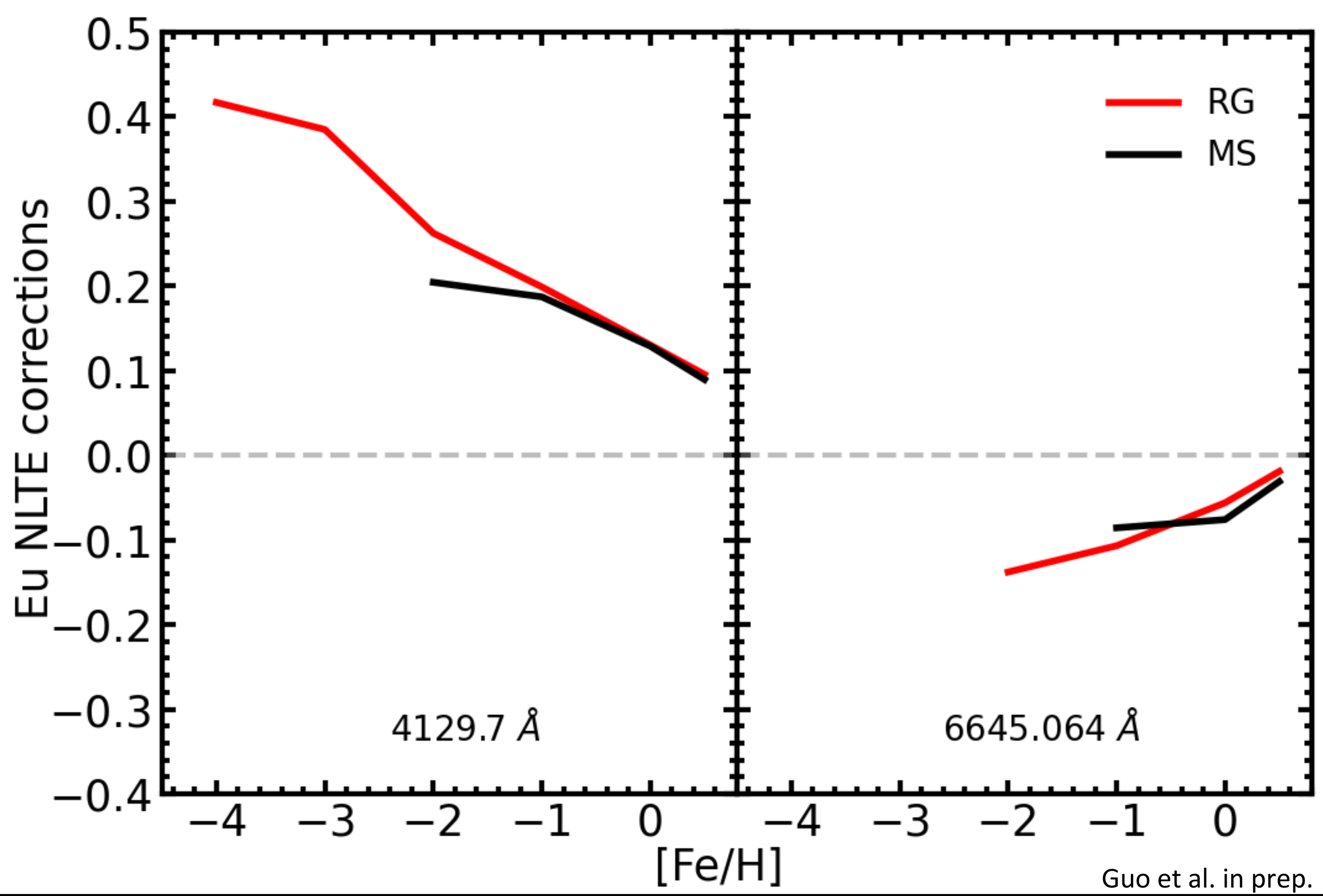


Storm et al. in prep.

Europium

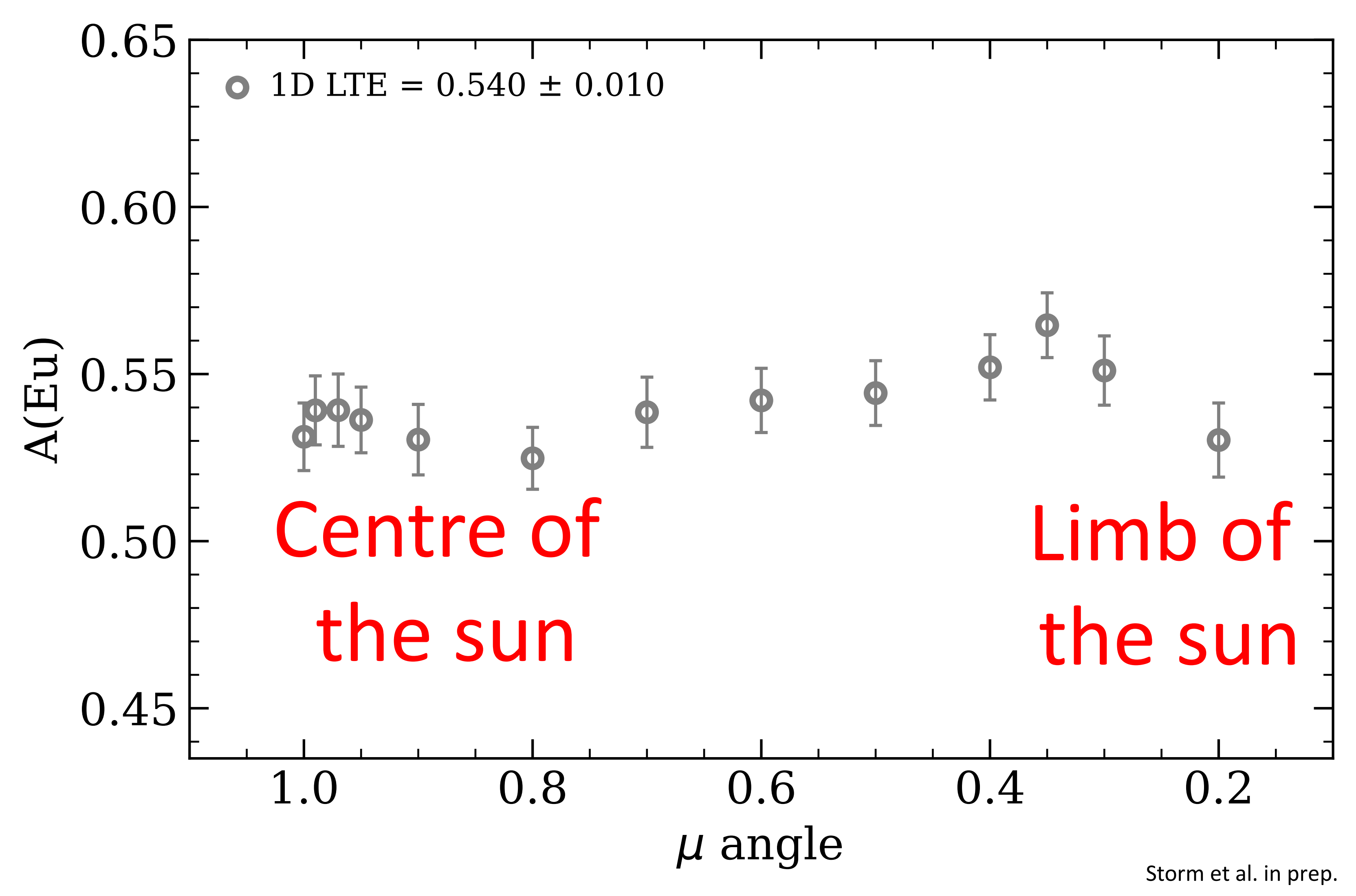
Europium (1D)

- Mainly r-process element
- New model atom with some quantum-mechanical rates

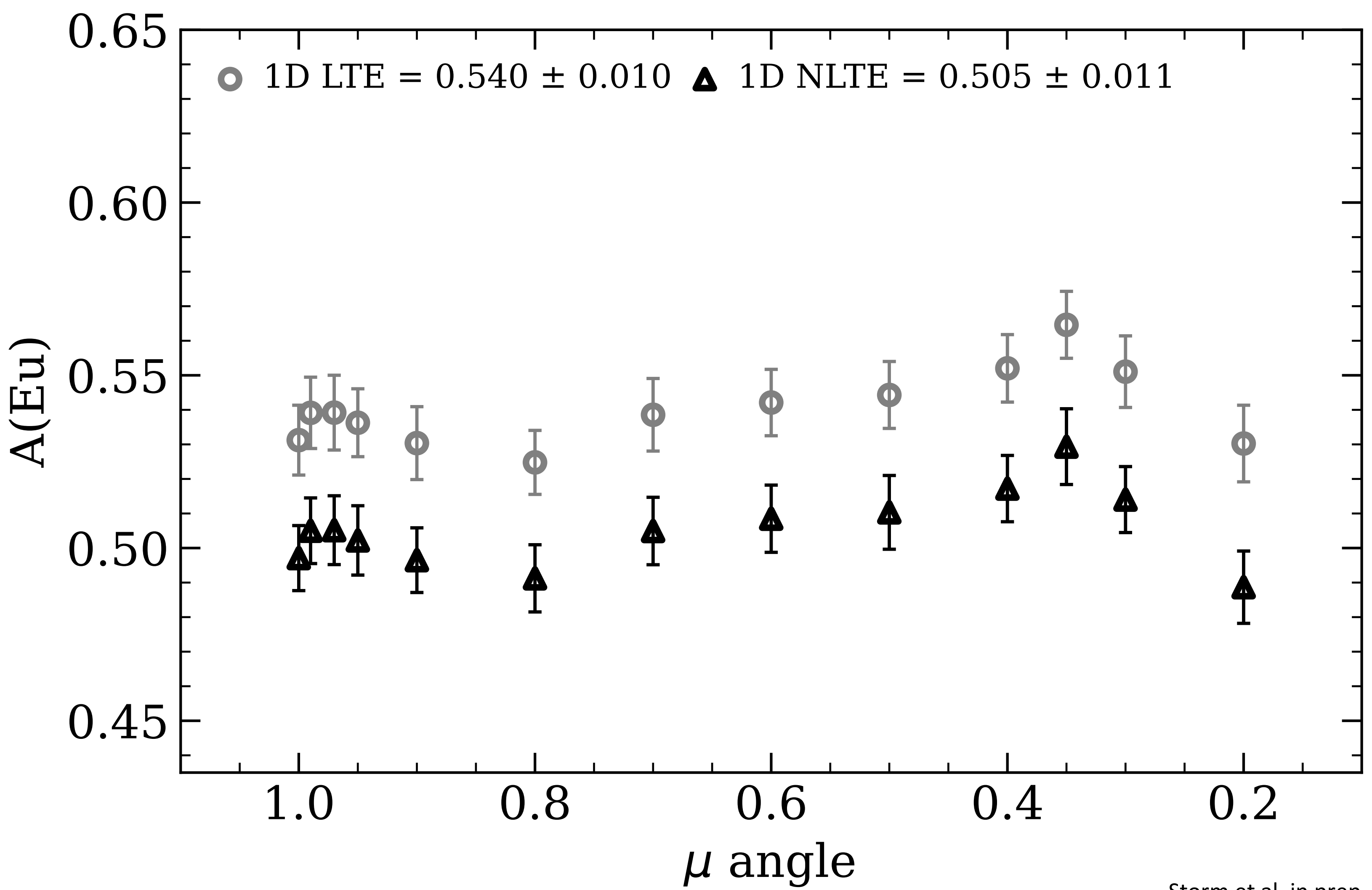


Guo et al. in prep.

CLV variation (3D)

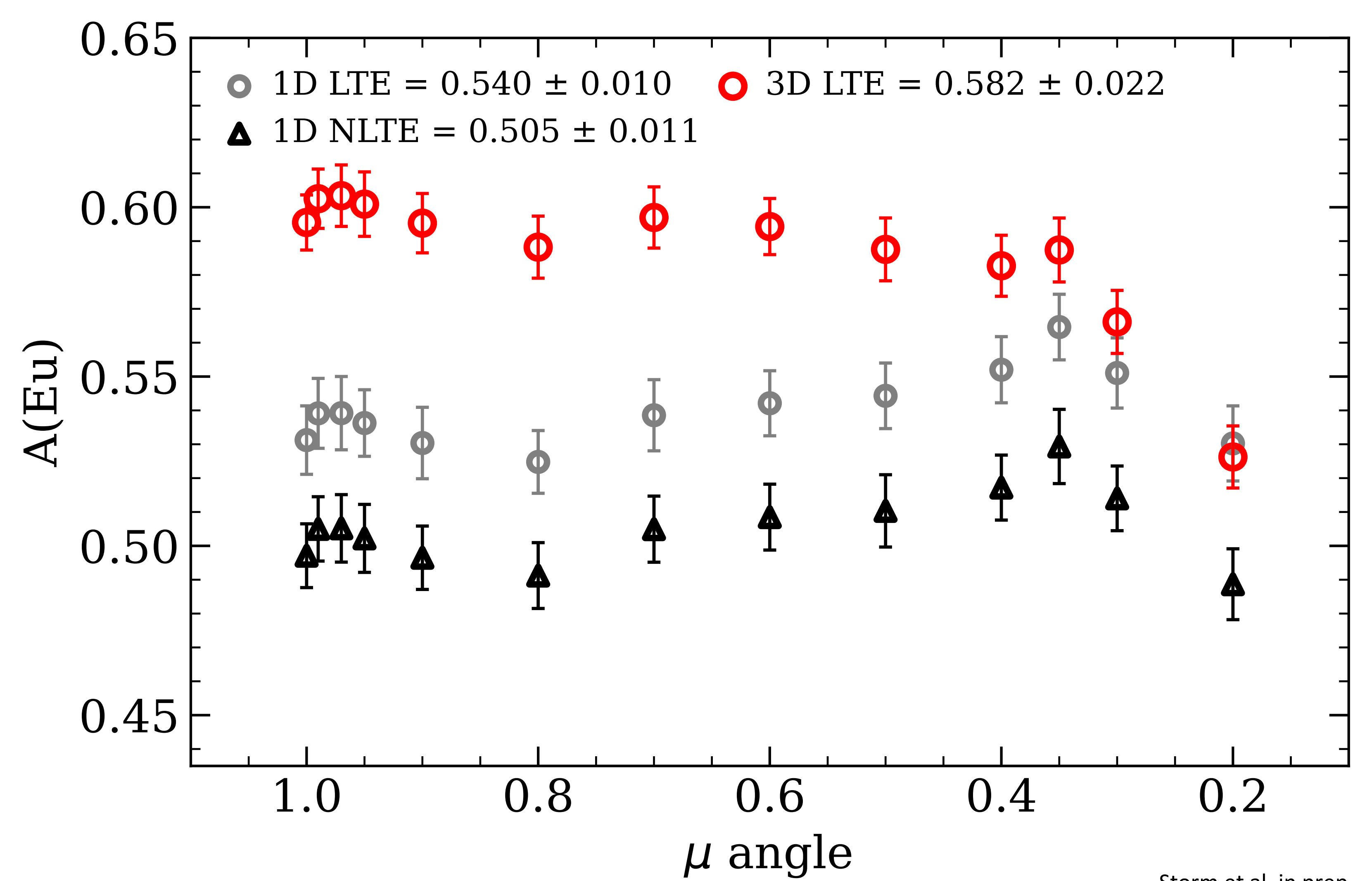


CLV variation (3D)



Storm et al. in prep.

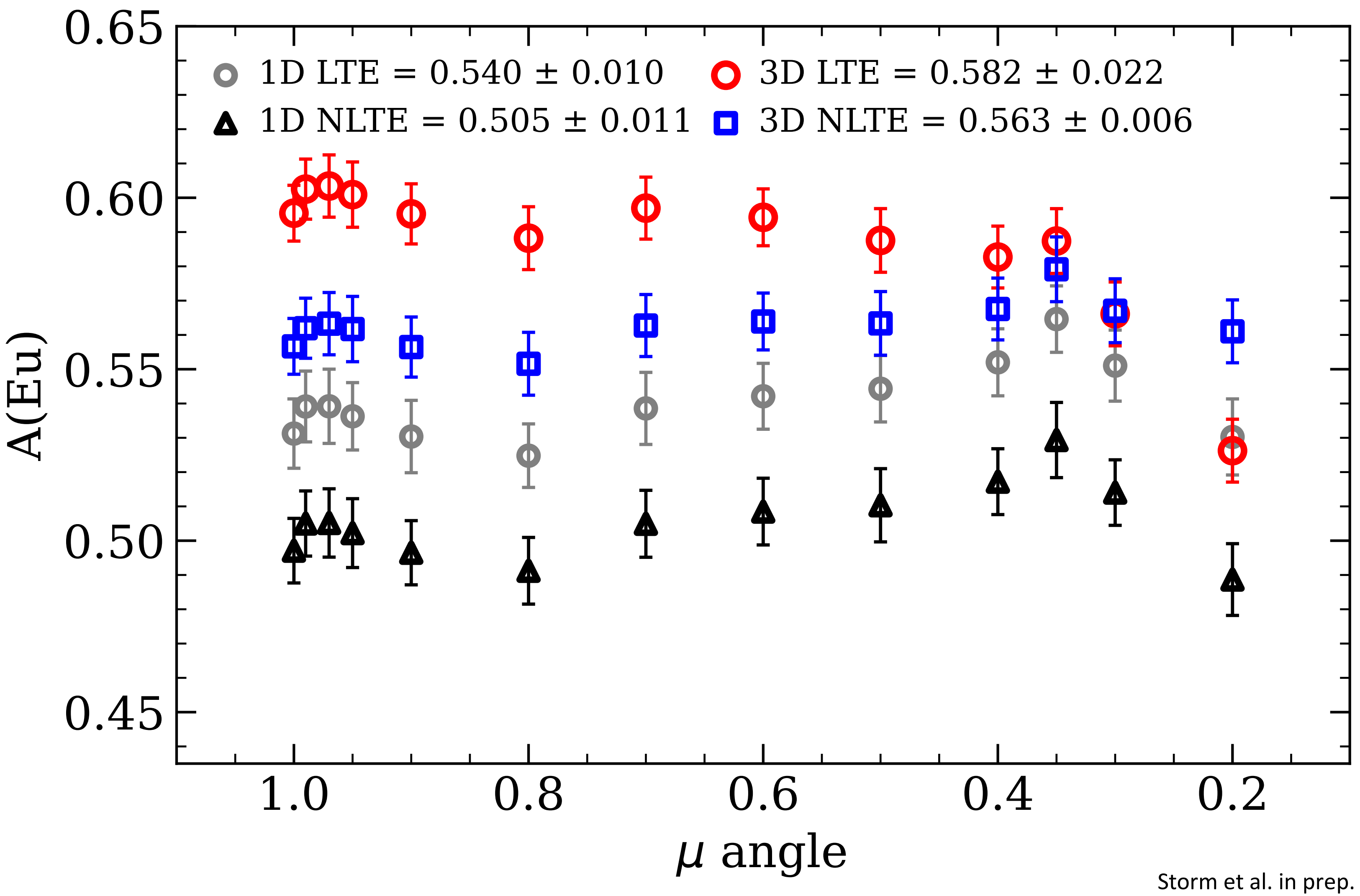
CLV variation (3D)



Storm et al. in prep.

CLV variation (3D)

- 3D NLTE: most consistent abundance
  - Lowest scatter
- Our solar **3D NLTE**:
  - A(Eu) = 0.56 ± 0.01
    - ± 0.07 systematic



Storm et al. in prep.

Conclusions

Conclusions

- NLTE and 3D modelling improves consistency of the results
- Y and Eu
  - NLTE effects especially important for near-UV lines
  - Higher for RG stars
- 3D NLTE
  - Most consistent results for center-to-limb variation
- Rederived solar Y and Eu abundances (**3D NLTE**):
  - A(Y) = 2.20 ± 0.04
  - A(Eu) = 0.56 ± 0.01
- You can also do fitting in NLTE: TSFitPy (GitHub)