


# 3D stellar simulations and spectra of the future

**Thomas Nordlander**

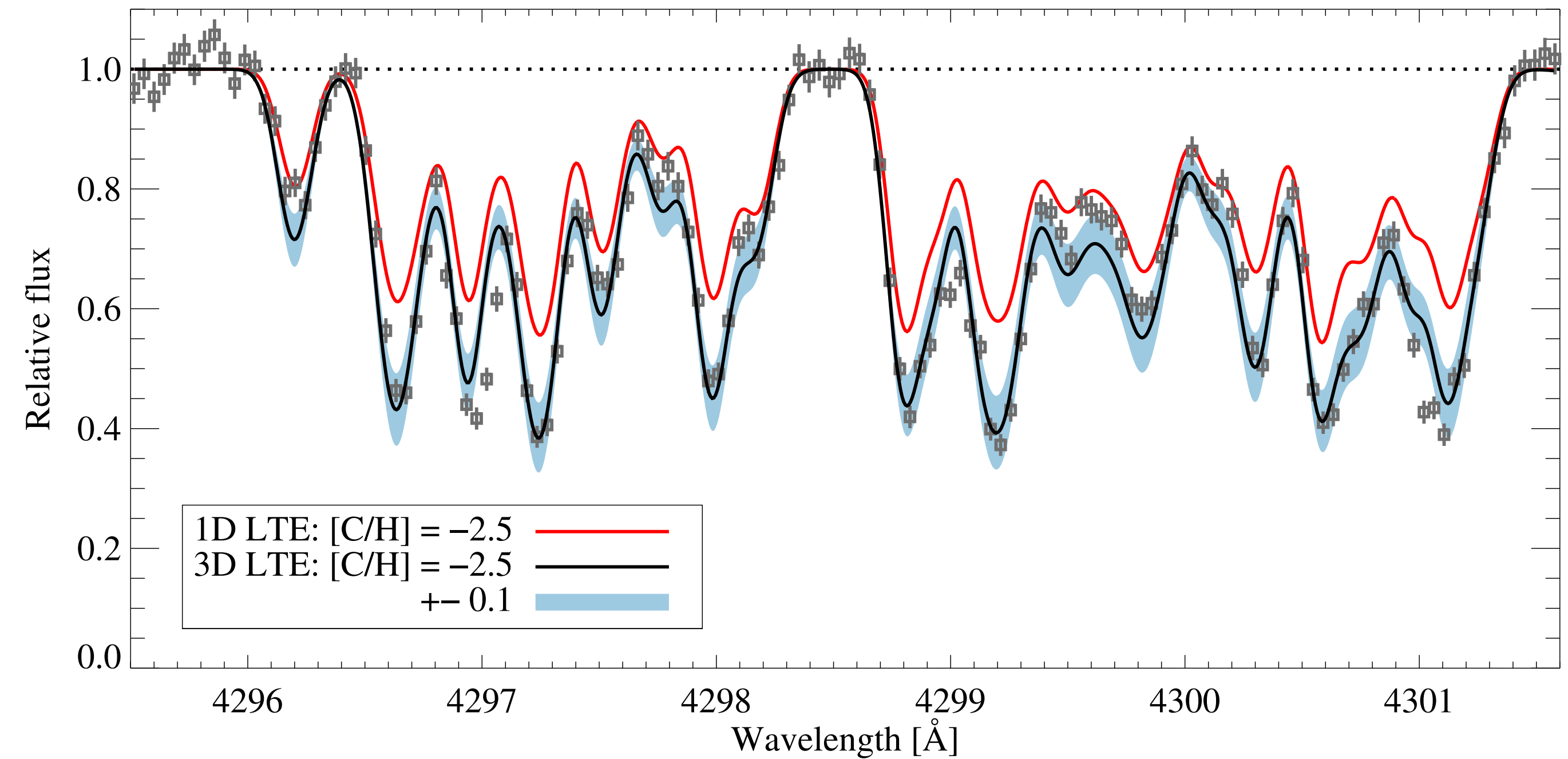
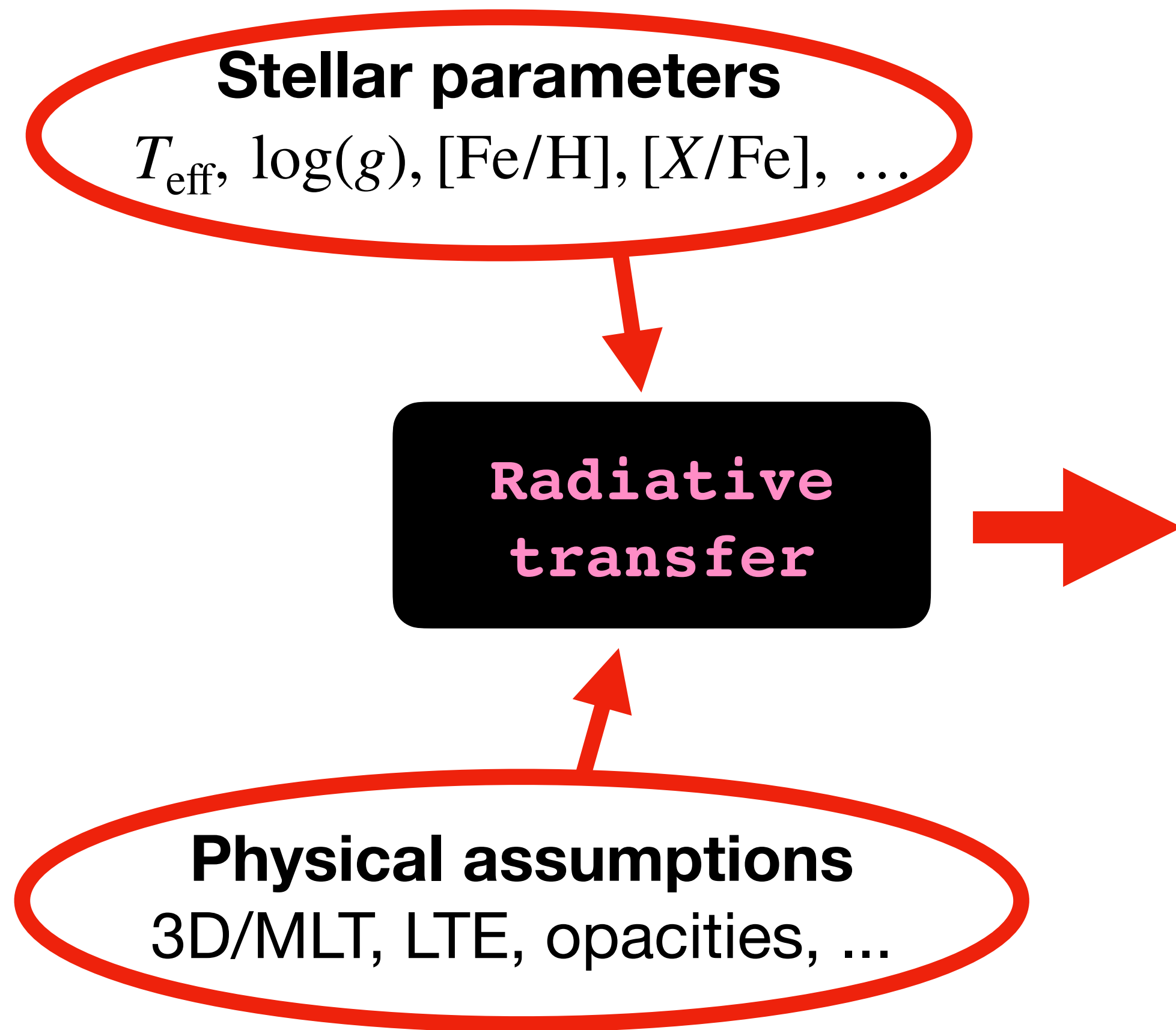
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The logo for the ARC Centre of Excellence for All Sky Astrophysics in 3D. It features the word "ASTRO" in a bold, purple, sans-serif font, followed by "3D" in a larger, stylized, purple font where the numbers are interconnected.

ARC CENTRE OF EXCELLENCE FOR ALL SKY ASTROPHYSICS IN 3D

# Abundances are not measured but *inferred*

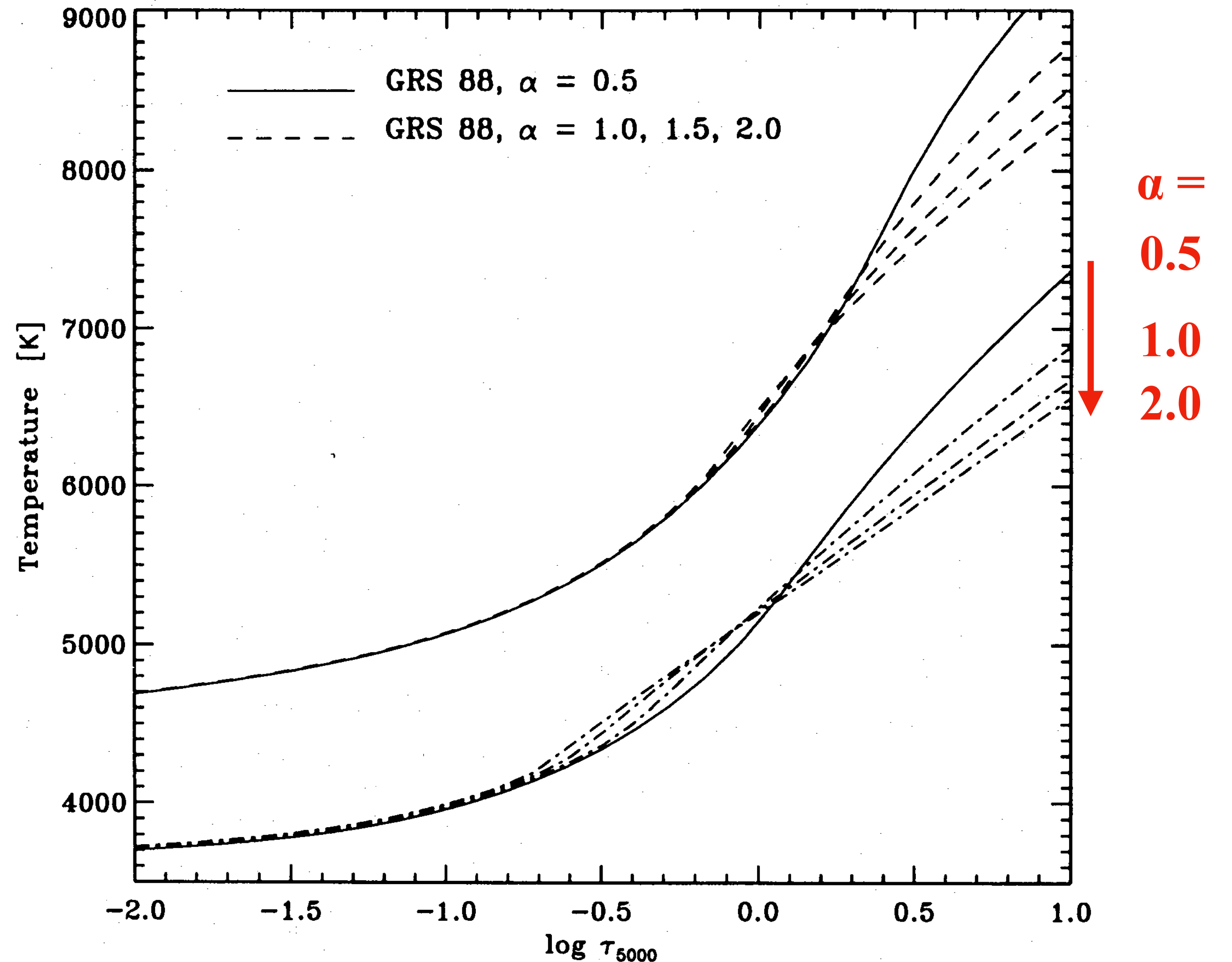


# Stellar atmospheres

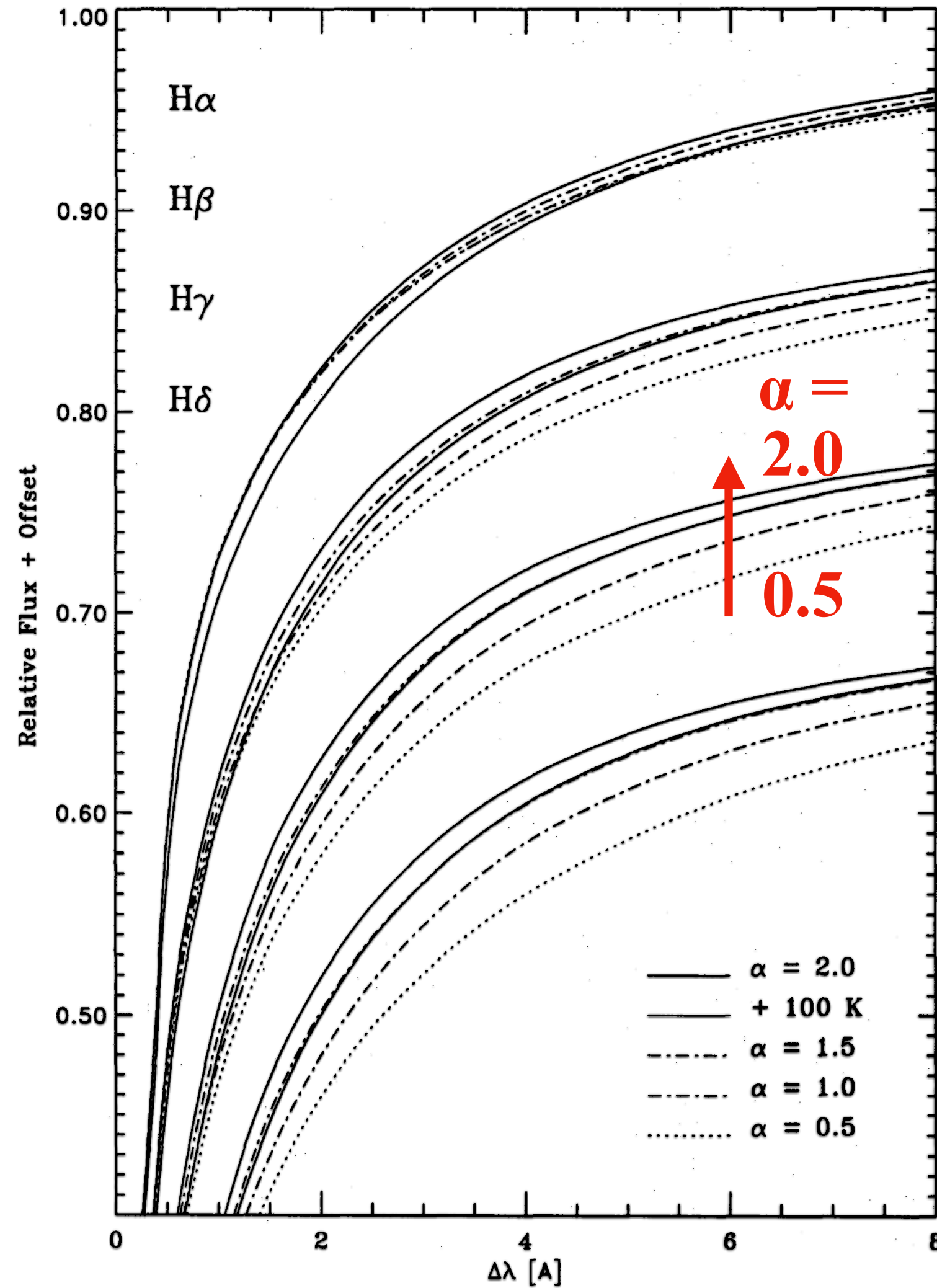
$$\mathcal{F}_{\text{tot}} = \mathcal{F}_{\text{rad}} + \mathcal{F}_{\text{conv}}$$

$$\mathcal{F}_{\text{conv}} \propto \alpha_{\text{MLT}} (\nabla_T - \nabla_{\text{ad}})$$

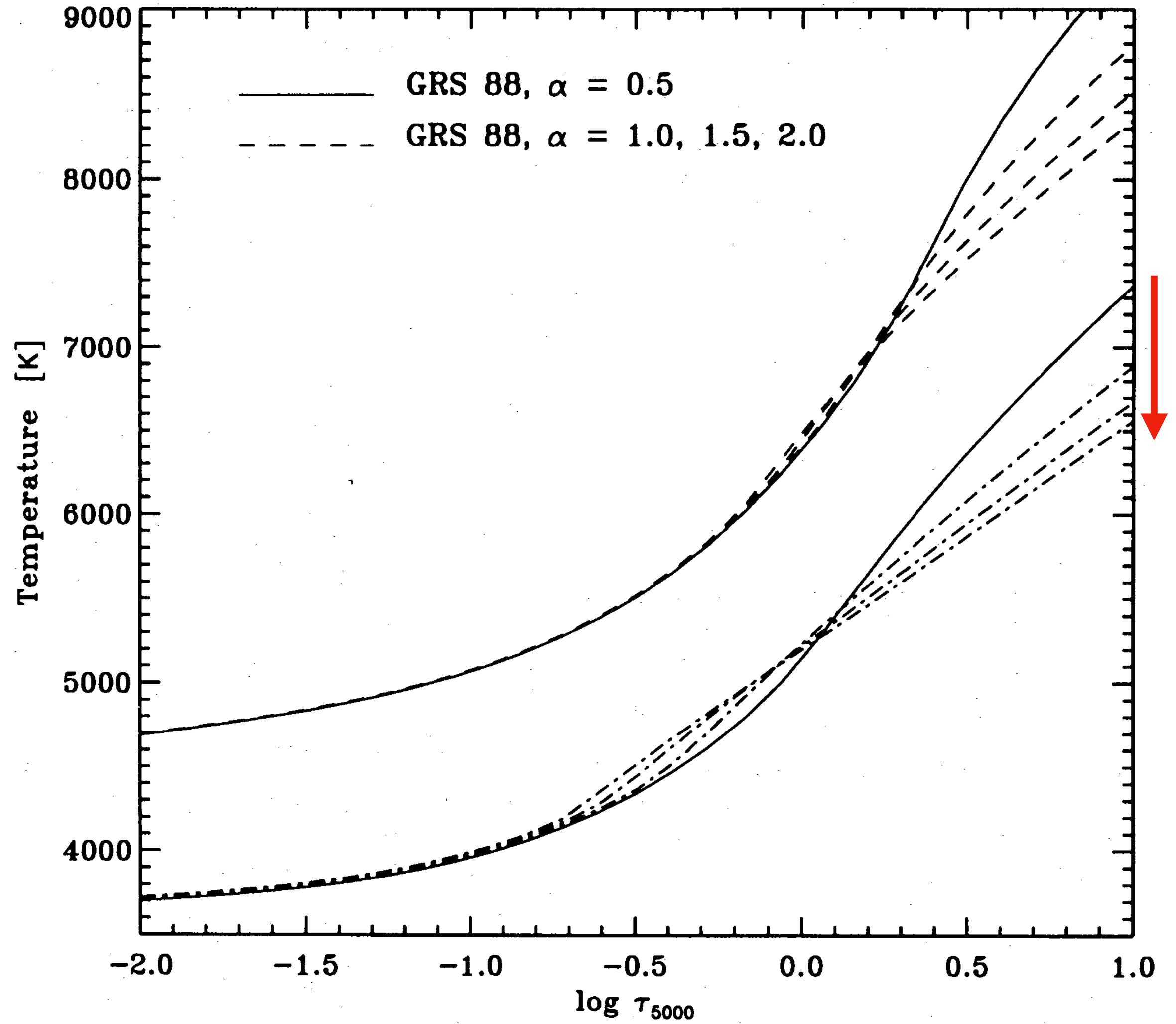
$$\alpha_{\text{MLT}} = \frac{l}{H_p} \quad \nabla_T = \frac{d \ln T}{d \ln P}$$



# MLT from spectroscopy: $\alpha \sim 0.5$



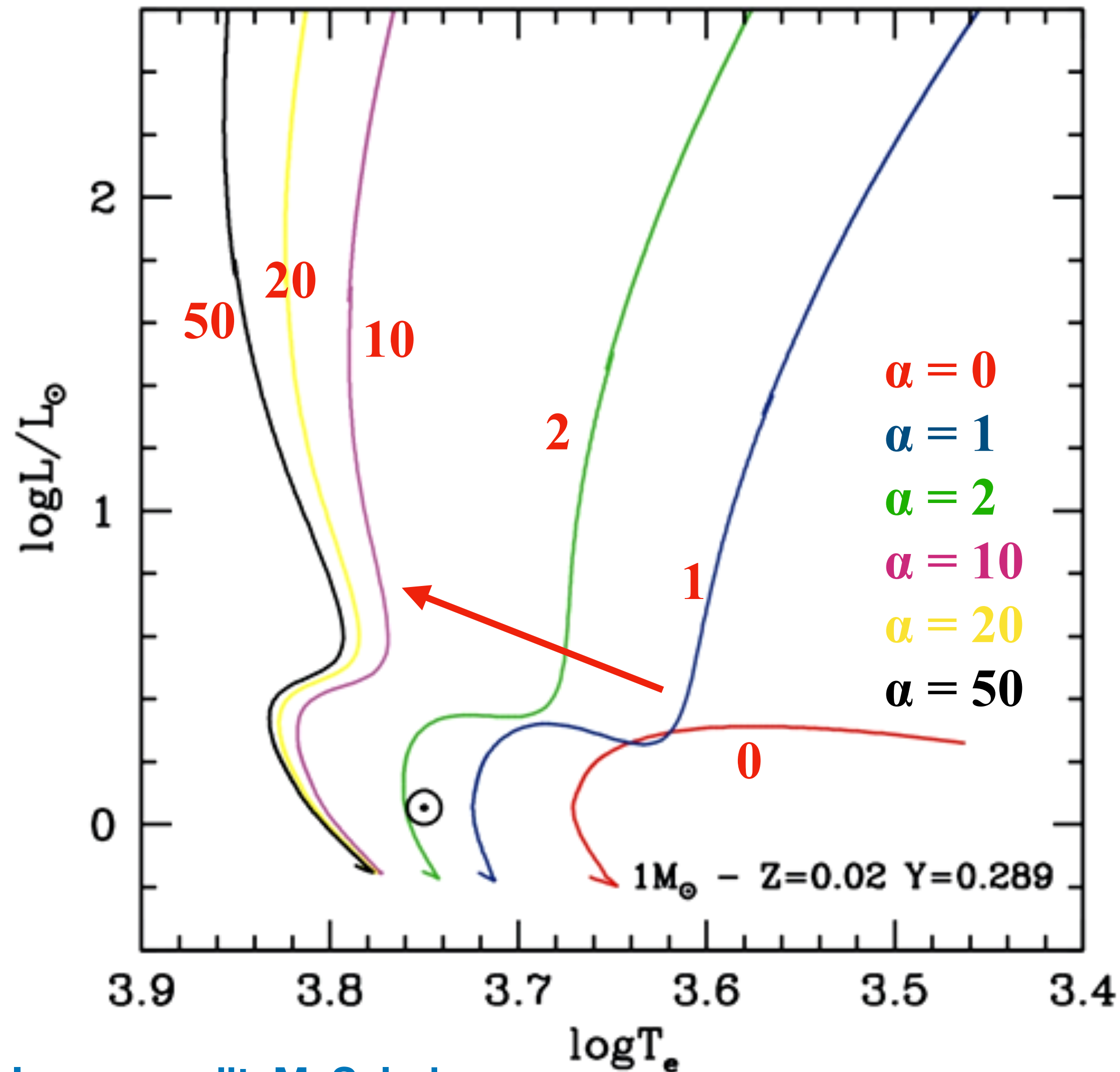
H $\alpha$   
H $\beta$   
H $\gamma$   
H $\delta$



$\alpha =$   
0.5  
1.0  
2.0

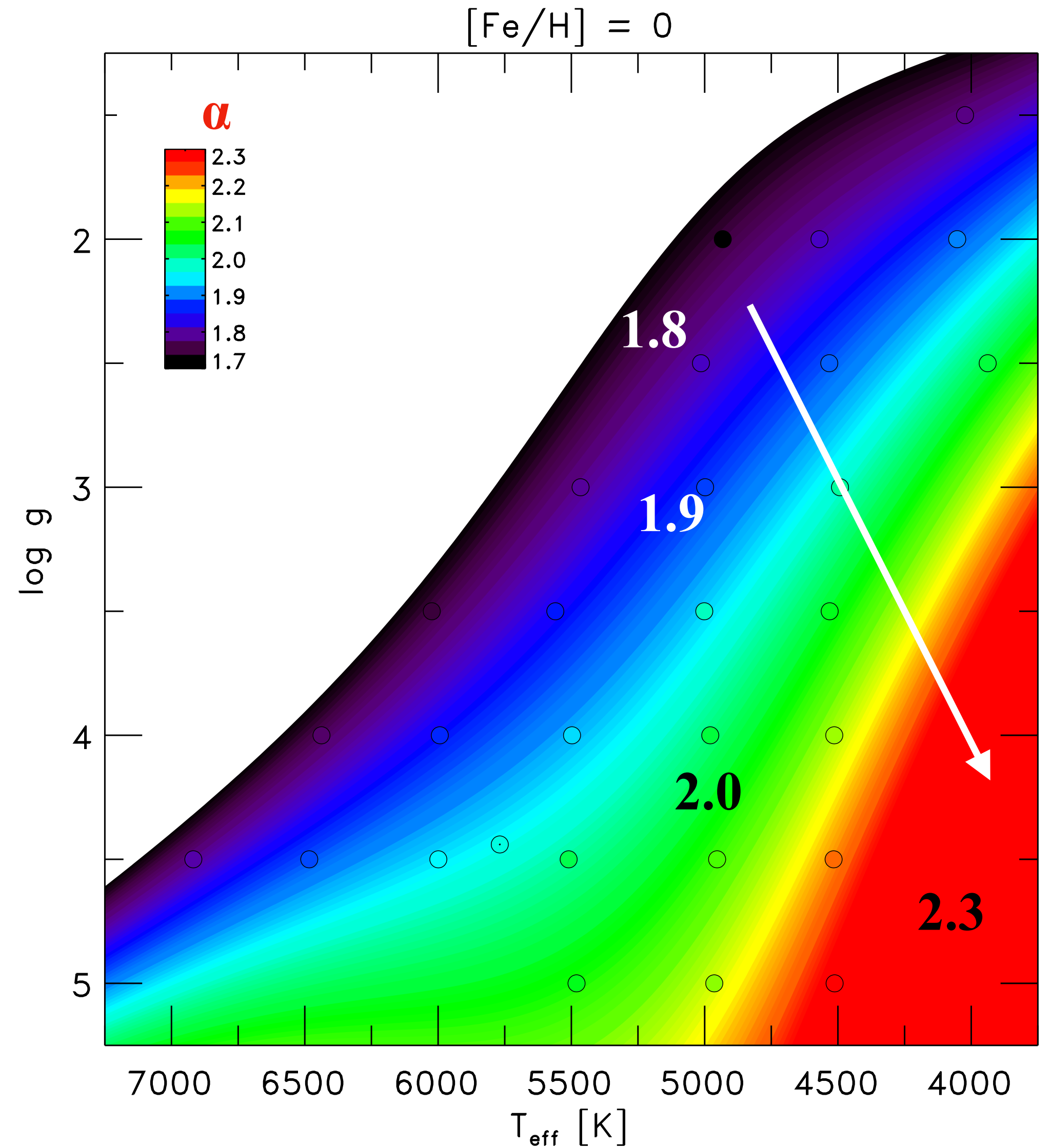
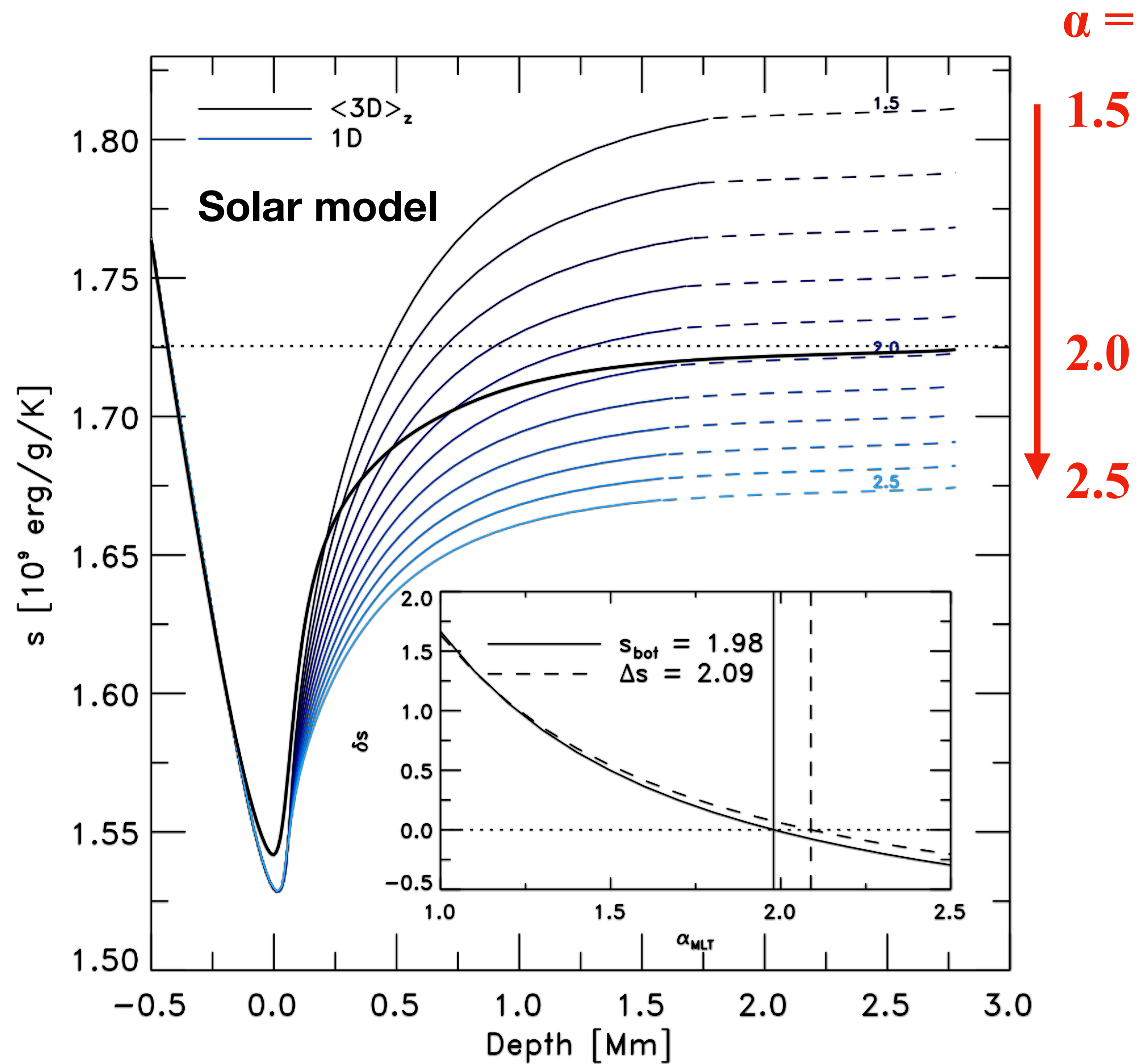


# MLT from stellar evolution: $\alpha \sim 2$



Code	Solar Z/X	$\alpha$
STARS	0.0262	2.09
STARS	0.0195	2.025
V-R	0.0181	2.007
Dartmouth	0.0266	1.938
BASTI	0.0280	1.913
MESA	0.0261	1.877
MESA	0.0207	1.783
Y <sup>2</sup>	0.0253	1.743
PARSEC	0.0252	1.740
Padova	0.0235	1.680
Geneva	0.0194	1.647

# MLT from 3D simulations: $\alpha \sim 2$



# Non-LTE (NLTE) = Statistical equilibrium

$$0 = \frac{dn_i}{dt} = \sum_{j \neq i} n_j (R_{ji} + C_{ji}) - n_i \sum_{j \neq i} (R_{ij} + C_{ij})$$

**Particle number**      **Incoming transitions**      **Outgoing transitions**

**Radiative transitions:**  $R_{ij} = A_{ij} + B_{ij} \bar{J}_\nu$

**Collisional transitions:**  $C_{ij}$

# Non-LTE (NLTE) = Statistical equilibrium

$$0 = \frac{dn_i}{dt} = \sum_{j \neq i} n_j (R_{ji} + C_{ji})$$

Particle  
number

Incoming transitions

Radiation field  
is non-local

Radiative transitions:

$$R_{ij} = A_{ij} + B_{ij} \bar{J}_\nu$$

Collisional transitions:

$$C_{ij}$$

Collisions  
are local

T [K]

9000  
8000  
7000  
6000  
5000  
4000

Solar model atmosphere

$\lambda = 200 \text{ nm}$

Radiation field

$T_{\text{eff}}$

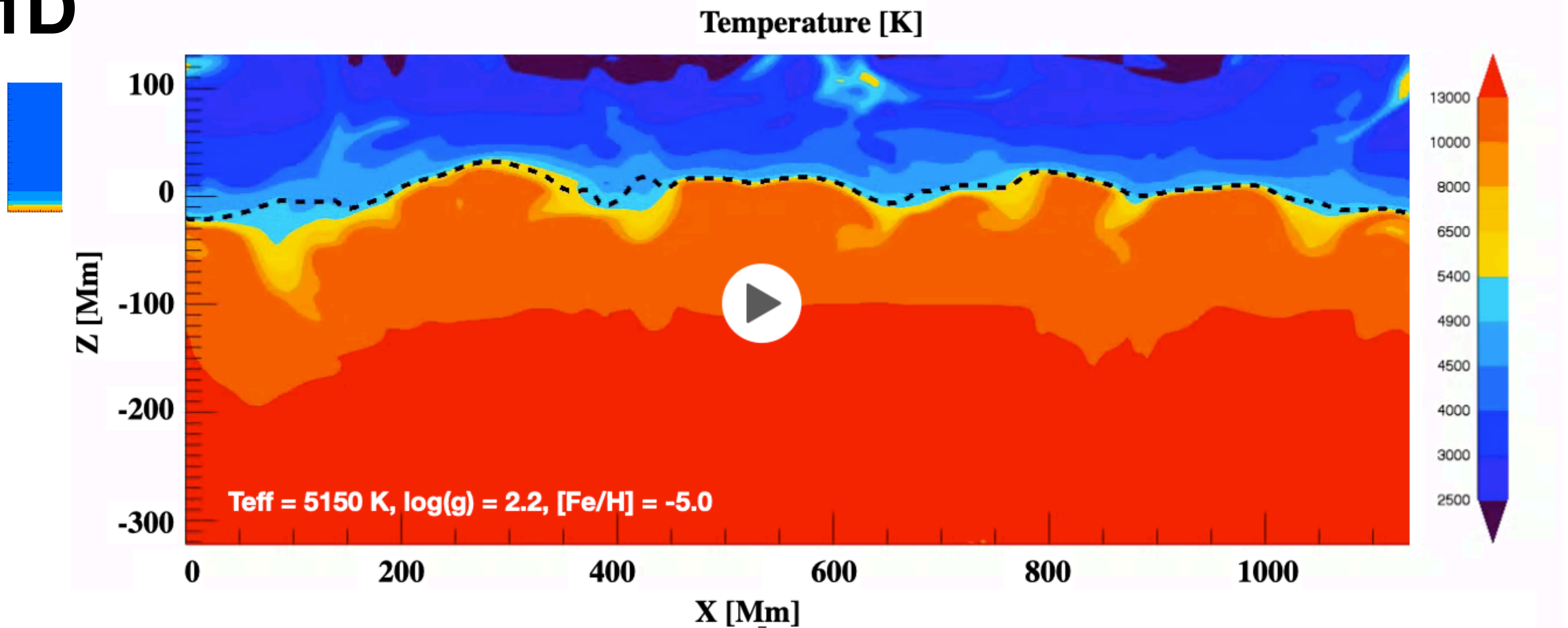
Gas

750 500 250 0 -250  
Height [km]



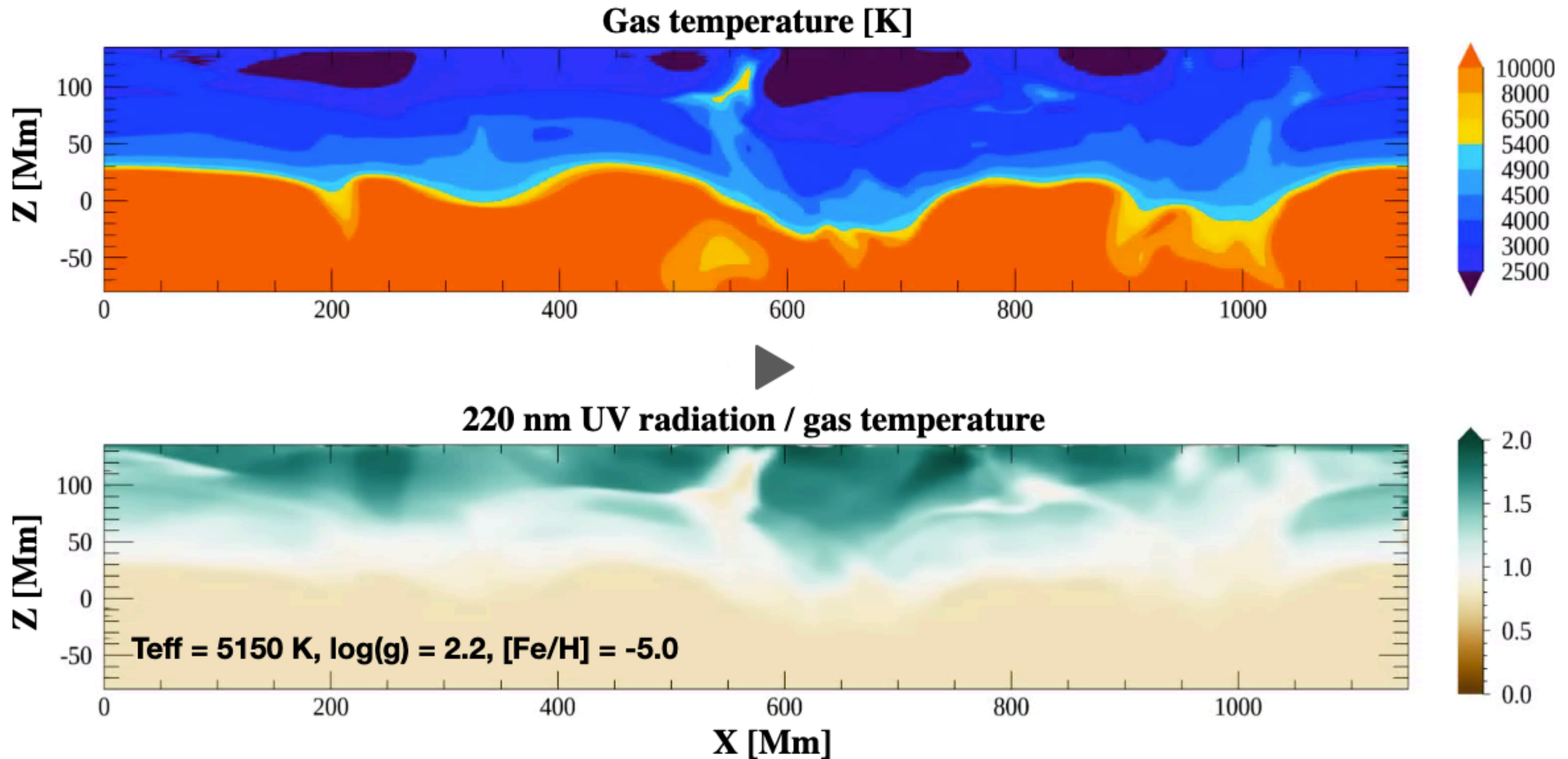
# Radiation+convection in stellar atmospheres

## 1D



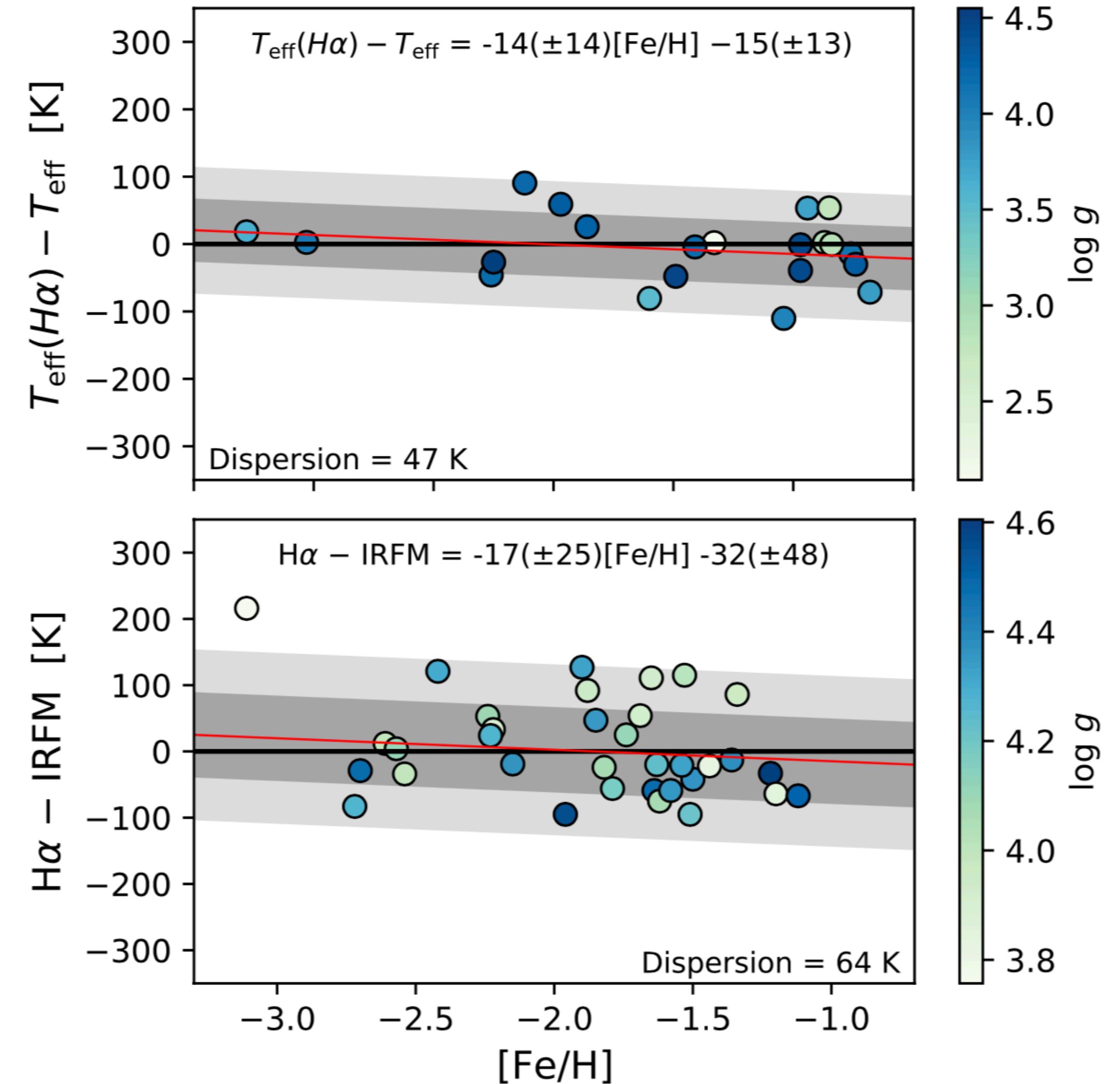
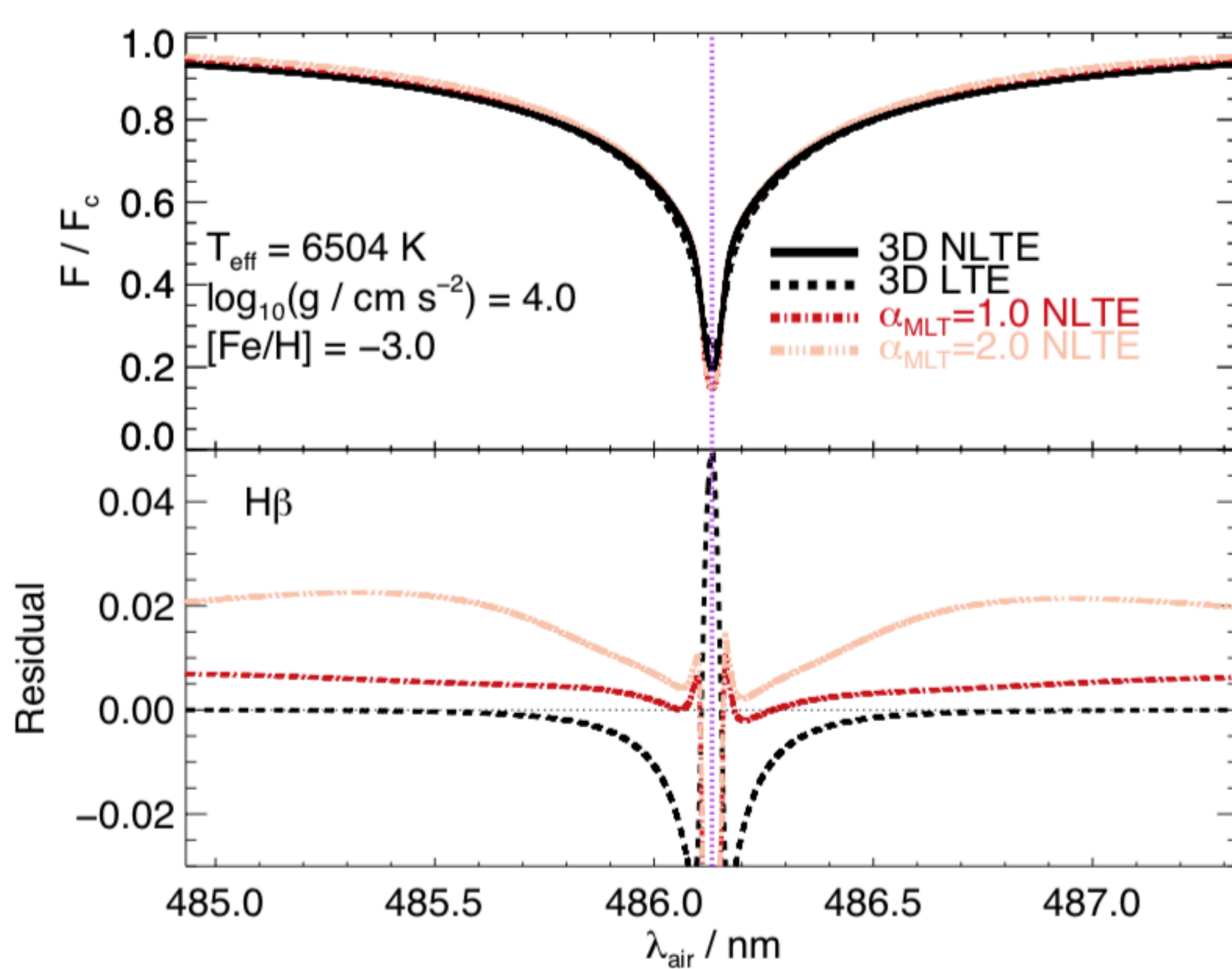


# Radiation+convection in stellar atmospheres



$$0 = \frac{dn_i}{dt} = \sum_{j \neq i} n_j (R_{ji} + C_{ji}) - n_i \sum_{j \neq i} (R_{ij} + C_{ij}) \quad R_{ij} = A_{ij} + B_{ij} \bar{J}_\nu$$

# 3D NLTE grid for Hydrogen



Grid available on CDS & Zenodo  
**Amarsi, Nordlander, Barklem+ 2018**

TITANS metal-poor reference stars  
**Giribaldi, da Silva, Smiljanic+ 2021**



# 3D NLTE calculations at $[\text{Fe}/\text{H}] < -6$

11

**Intensity contrast**

**Li I 6707 Å**

**Mg I 5183 Å**

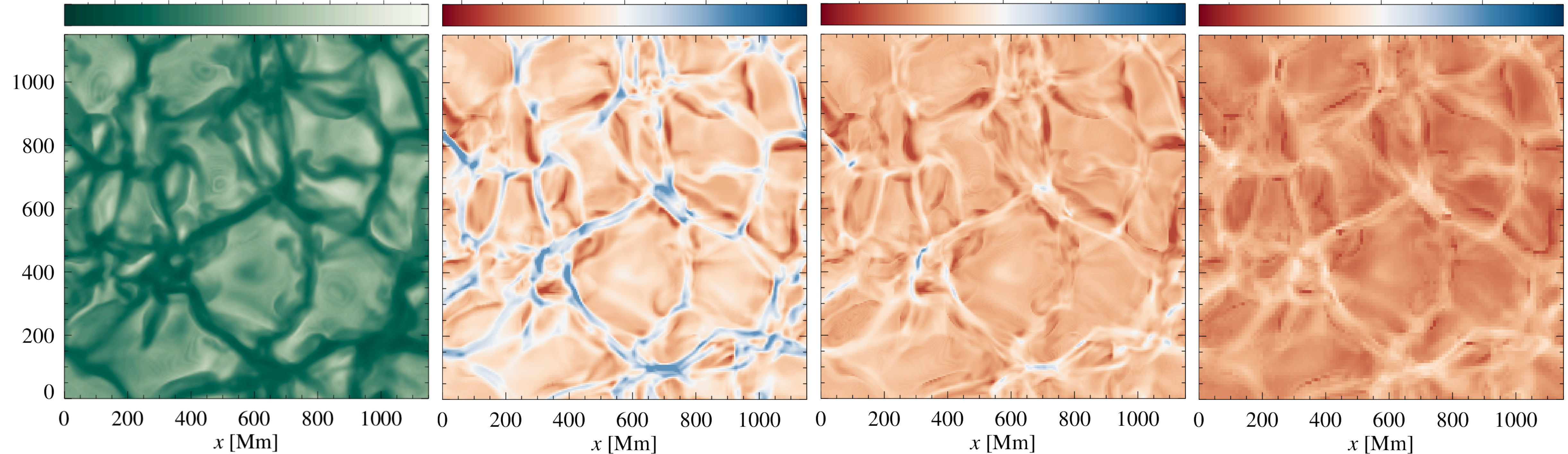
**Fe I 3719 Å**

$I_c / \langle I_c \rangle$   
0.6 0.8 1.0 1.2 1.4 1.6

$\Delta \log W_{\lambda, \mu=1} (\text{NLTE} - \text{LTE})$   
-0.4 -0.2 0.0 0.2 0.4

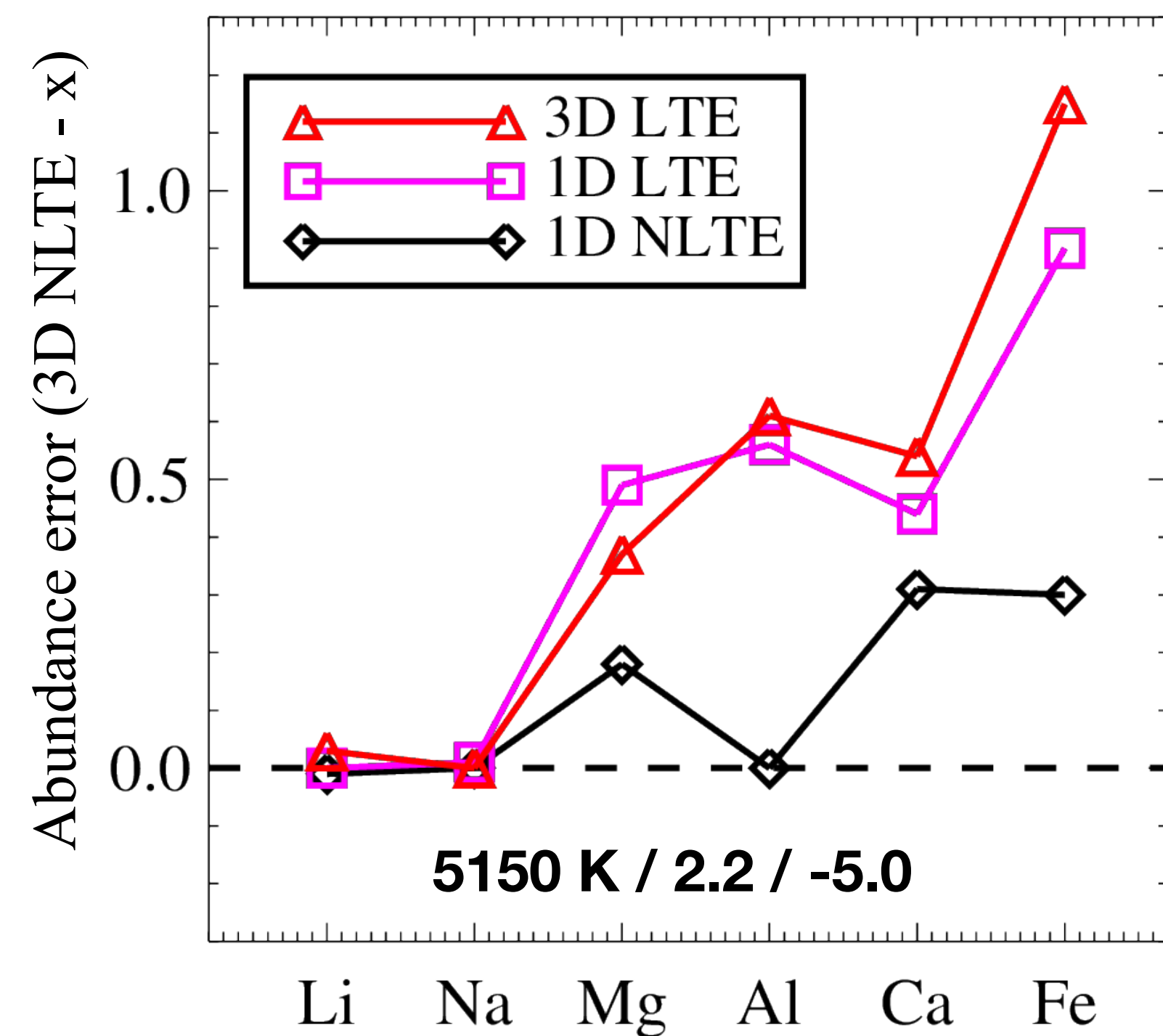
$\Delta \log W_{\lambda, \mu=1} (\text{NLTE} - \text{LTE})$   
-0.2 0.0 0.2

$\Delta \log W_{\lambda, \mu=1} (\text{NLTE} - \text{LTE})$   
-1 0 1

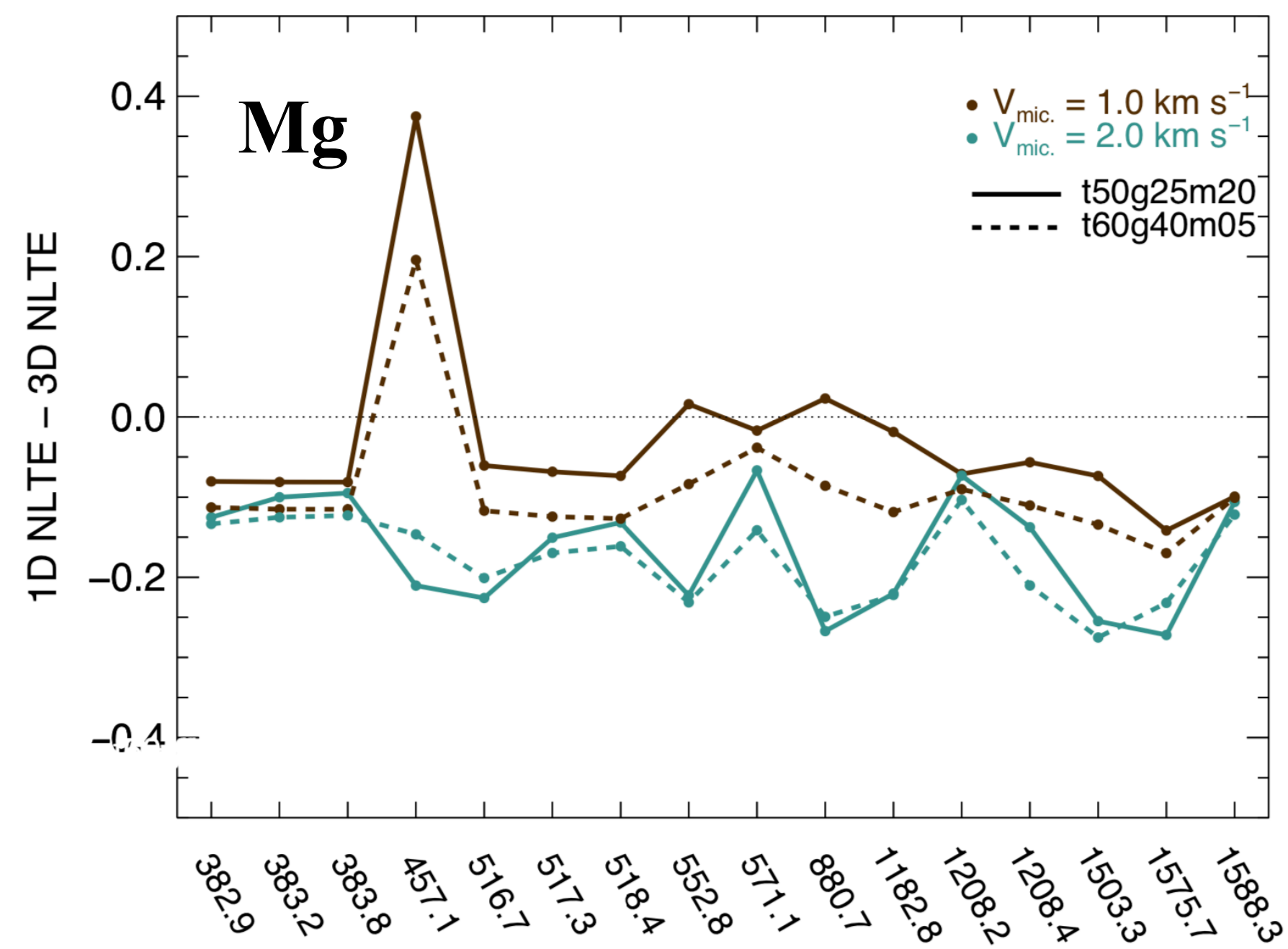


(Keller's star SMSS 0313-6708)  
**Nordlander, Amarsi, Lind+ 2017**

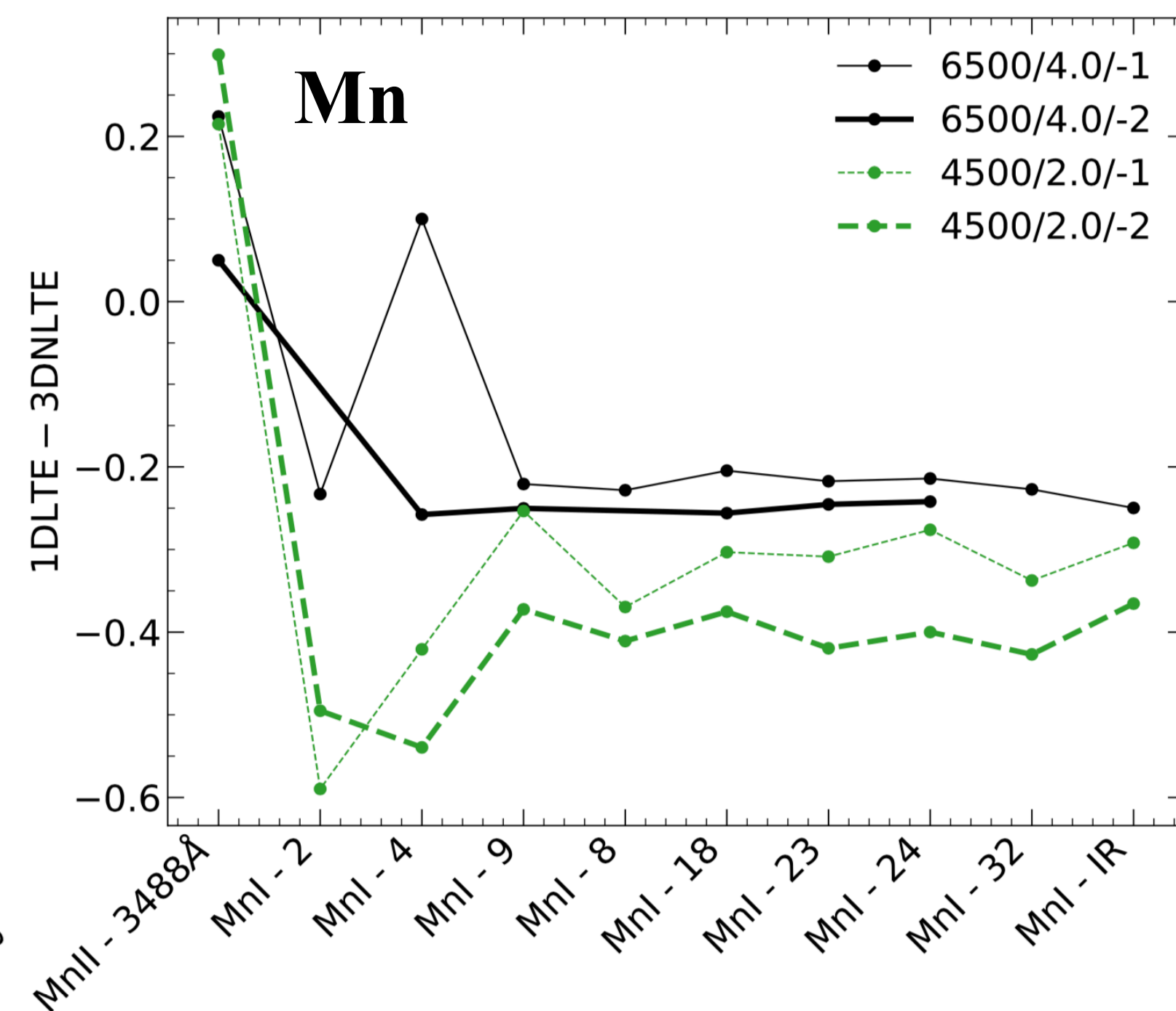
# 3D NLTE abundance corrections



Nordlander, Amarsi, Lind+ 2017



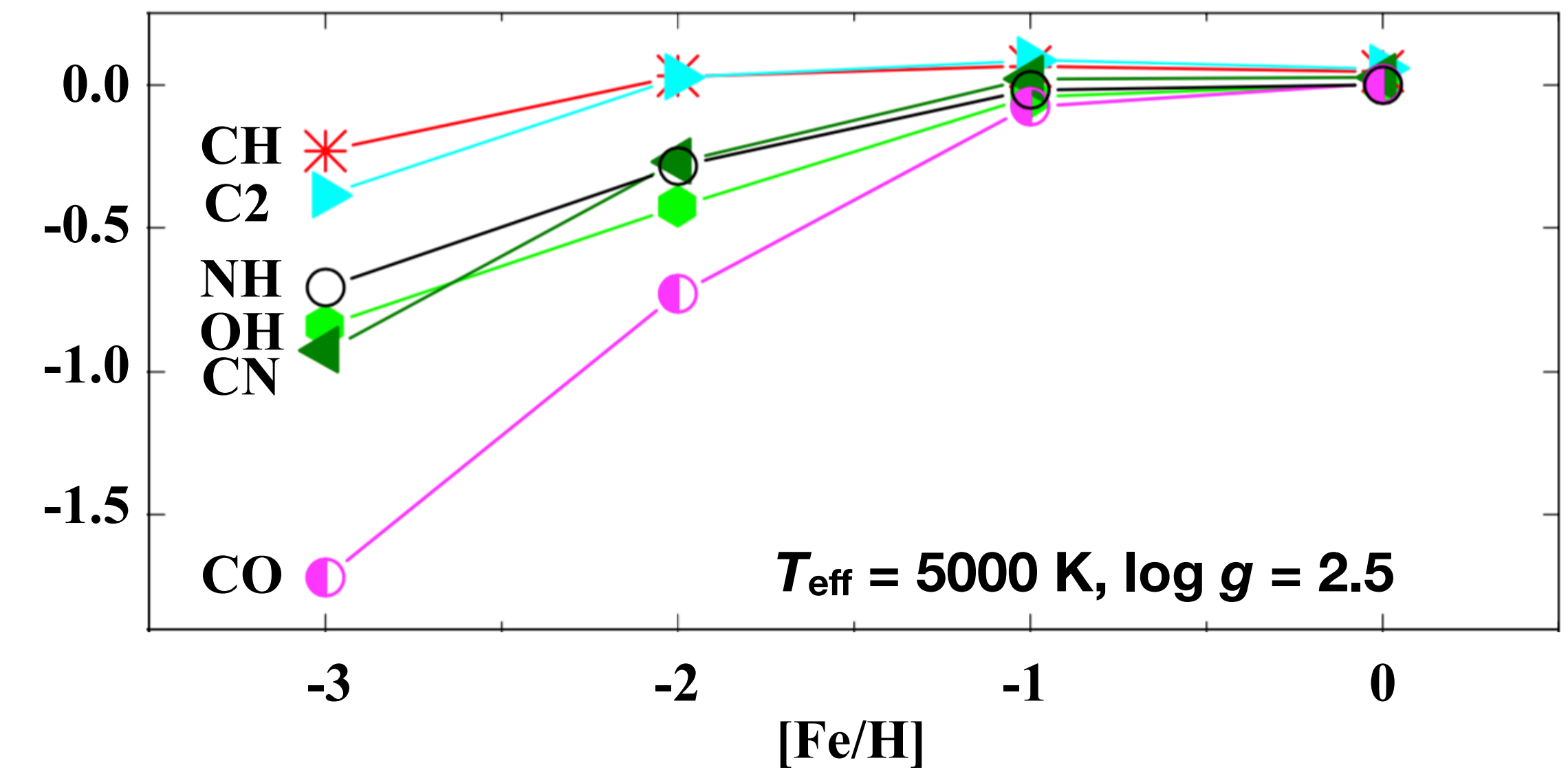
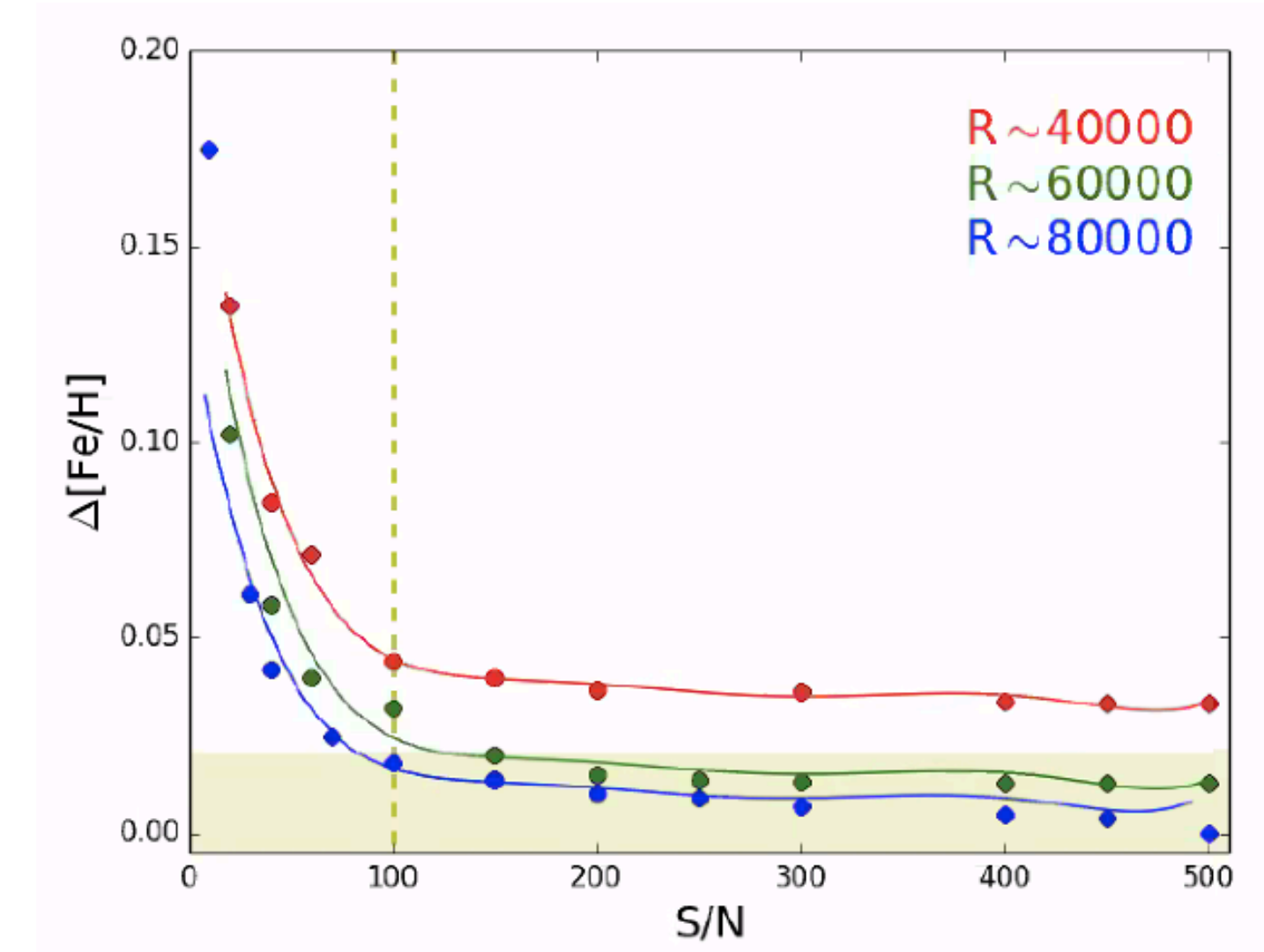
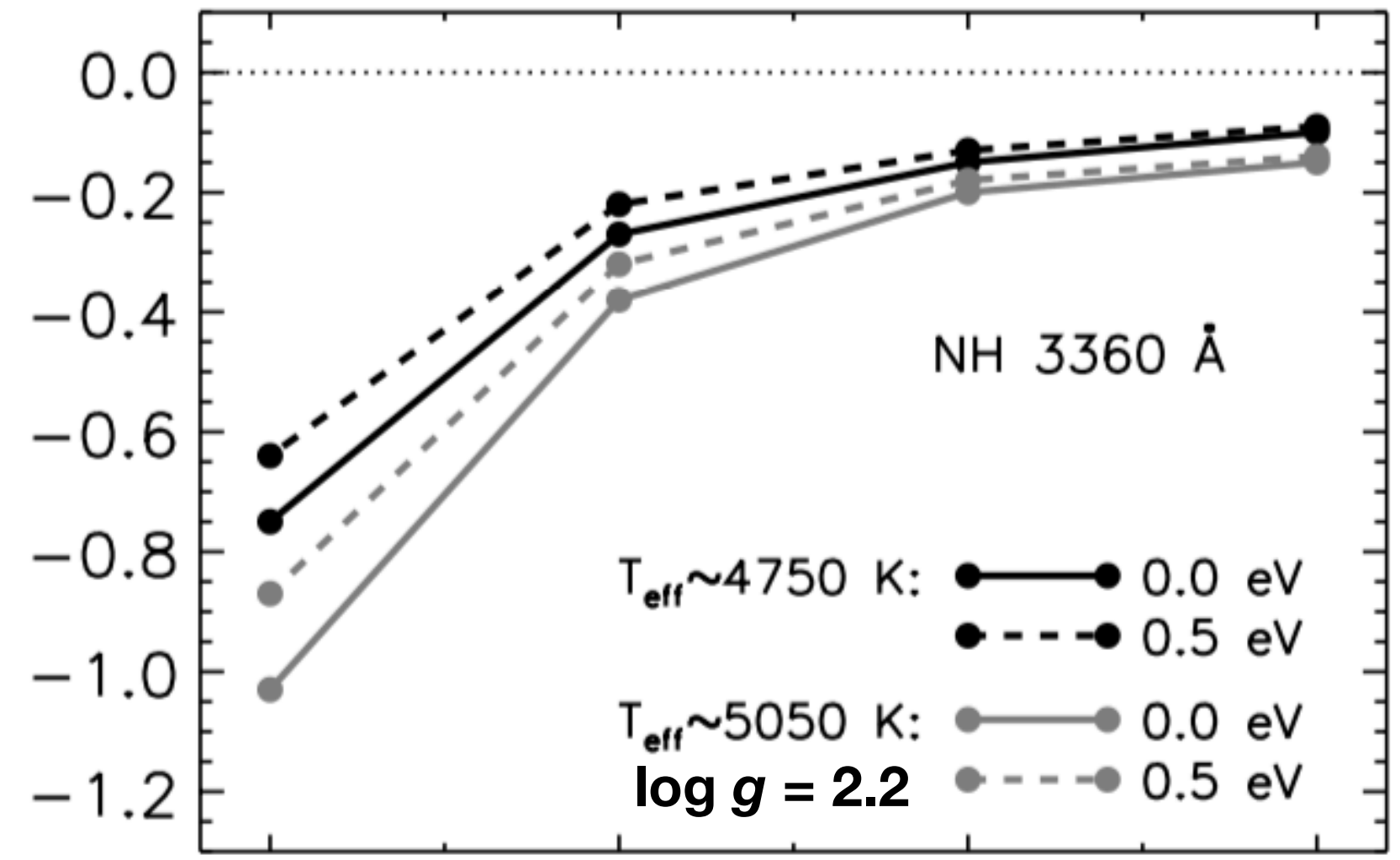
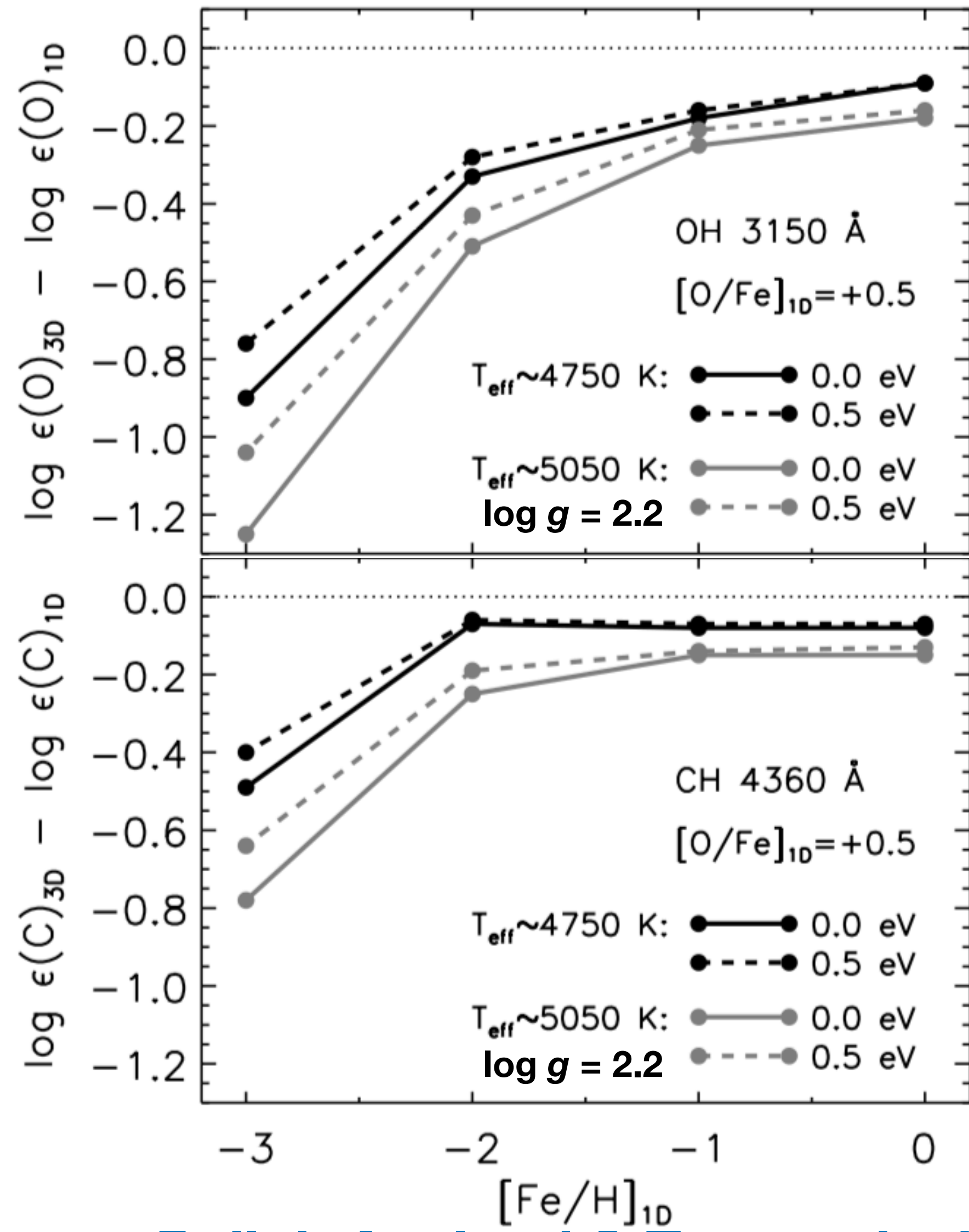
Bergemann, Collet, Amarsi+ 2017



Bergemann, Gallagher, Eitner+ 2019



# 3D spectra of molecular lines in giants

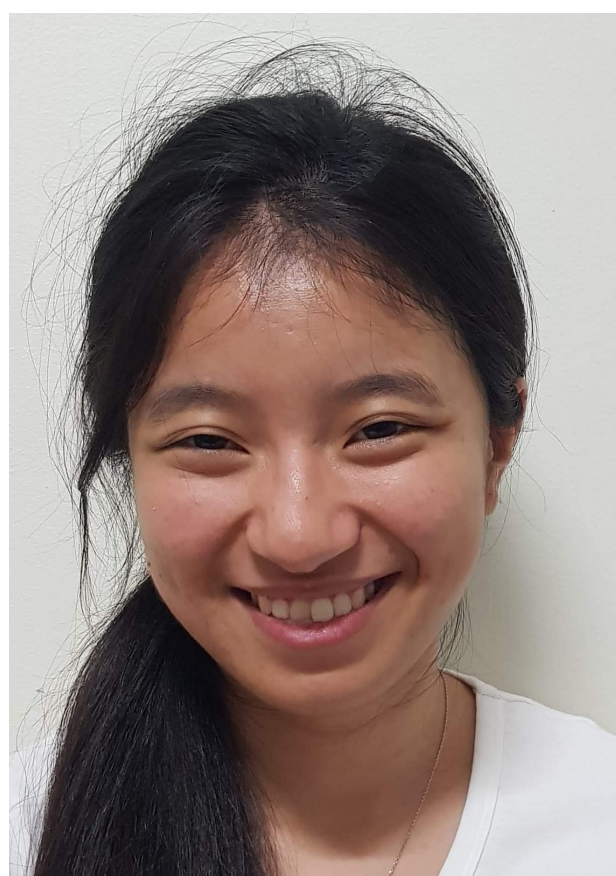
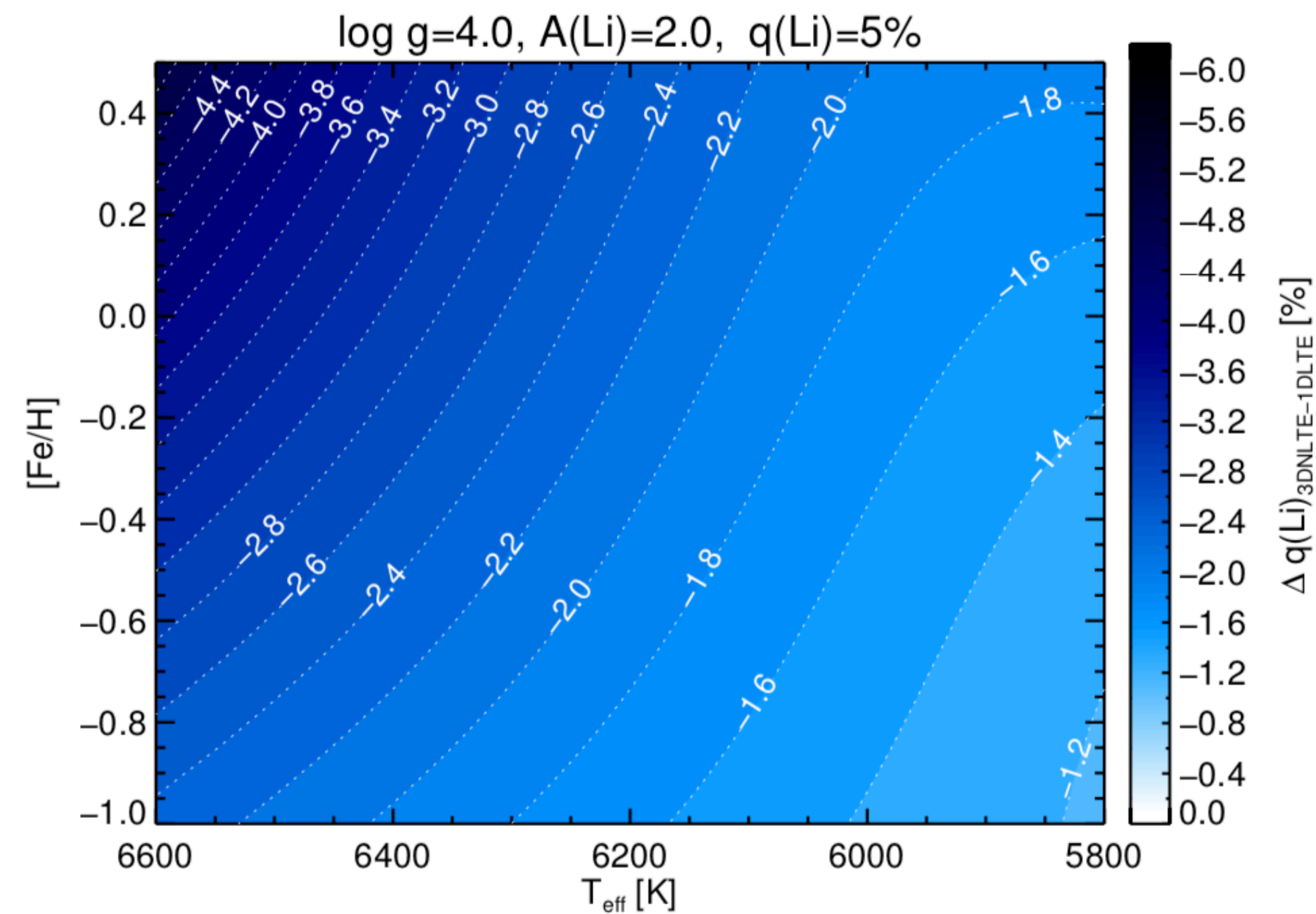
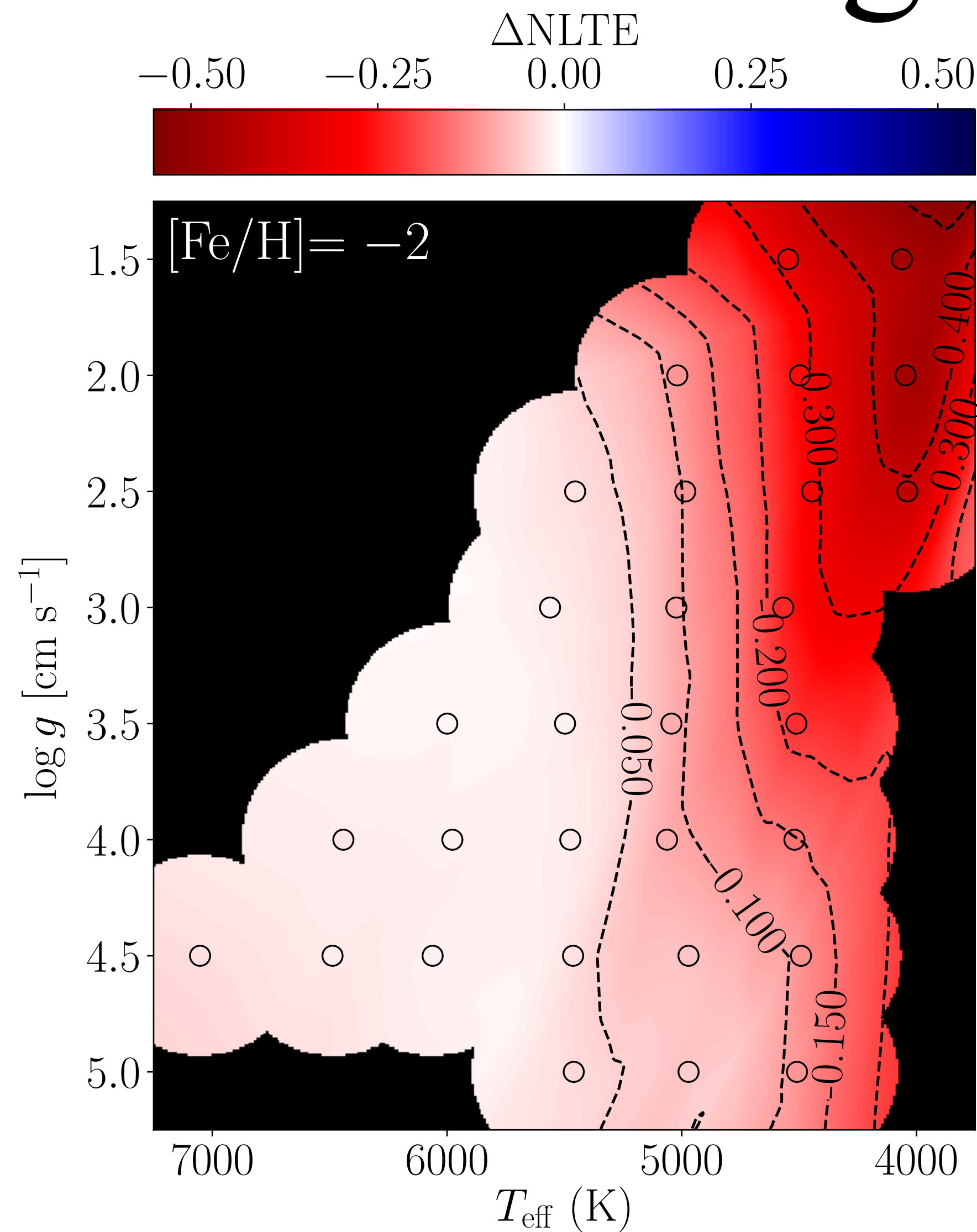


Collet, Asplund & Trampedach 2007

Dobrovolskas, Kučinskas, Steffen+ 2013



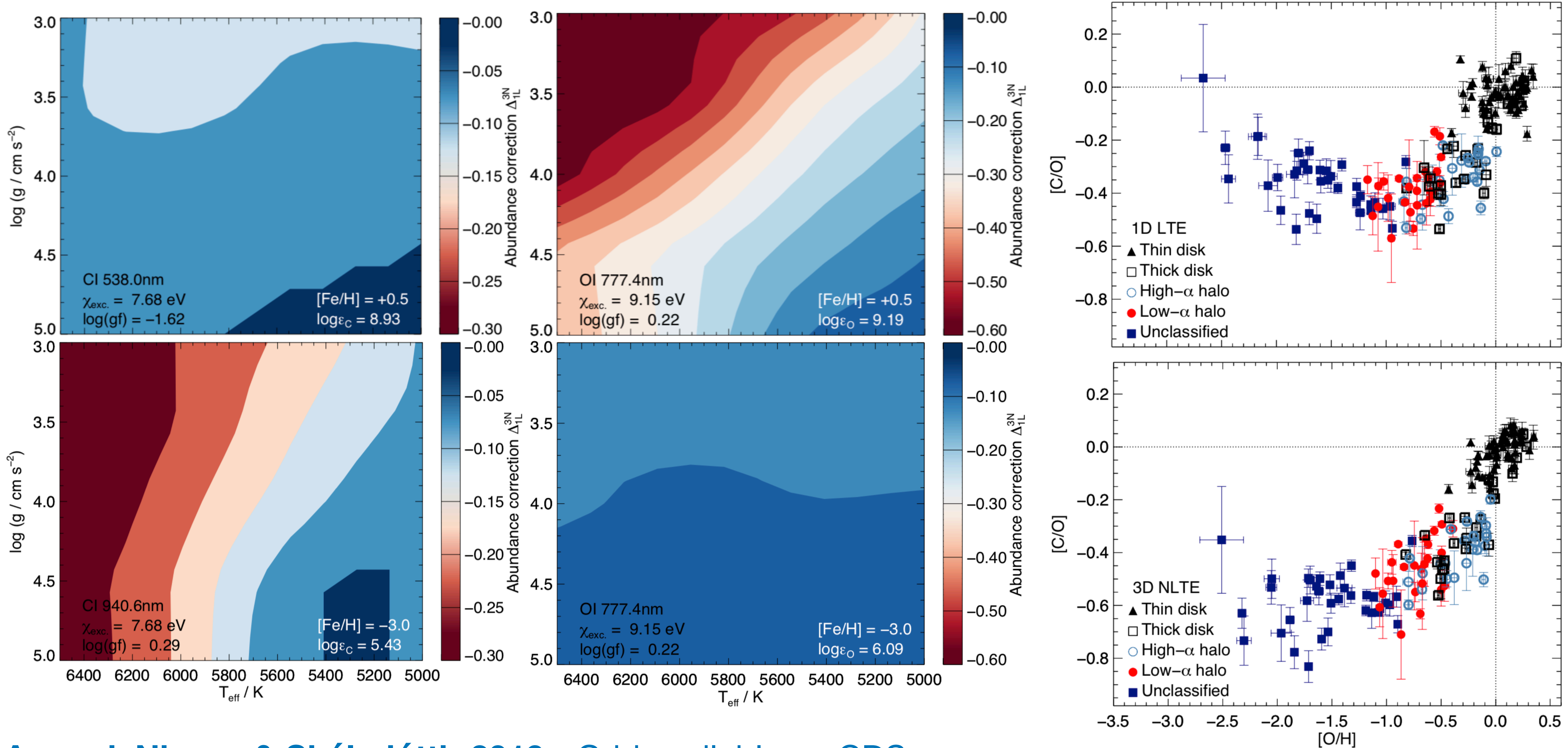
# 3D NLTE grids for Lithium



Ella (Xi) Wang, Nordlander+ 2021  
<https://github.com/ellawang44/Breidablik>

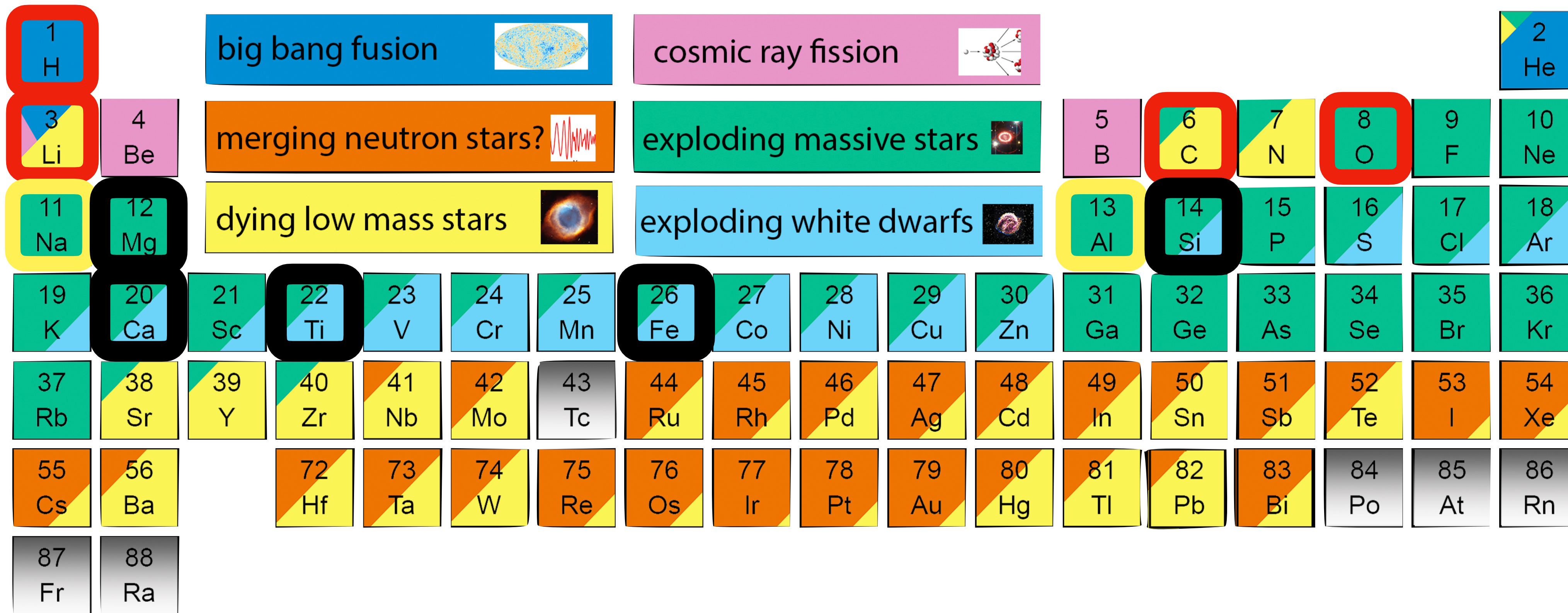
isotopes: Harutyunyan, Steffen+ 2018  
 abundances: Mott, Steffen+ 2020

# 3D NLTE grids for Carbon & Oxygen





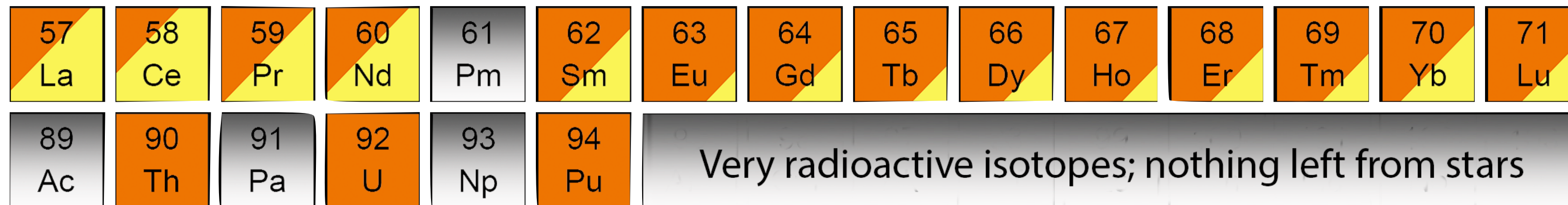
# Grids of 3D LTE/NLTE spectra



**Published**

**Just finished**

**In progress...**



# 3D / Non-LTE resources

## 3D atomic lines:

- H: Amarsi, Nordlander+ 2018
- Li: Harutyunyan, Steffen+ 2018 (6Li/7Li)  
Mott, Steffen+ 2020  
Wang, Nordlander+ 2021
- C & O: Amarsi, Nissen+ 2019
  
- Na, Al: Nordlander+ 2022
- Fe: Nordlander+ 2022 ( $[\text{Fe}/\text{H}] < -3$ )  
Amarsi+ 2022 ( $[\text{Fe}/\text{H}] \sim 0$ )
- Mg, Ca, Ti, ....: 2023?
- n-capture: 2025?

## 1D resources:

- [inspect-stars.com](http://inspect-stars.com) (Lind)  
Li, Na, Mg, Ca, Ti, Cr, Mn, Fe, Co, Sr, Ba
- [nlte.mpia.de](http://nlte.mpia.de) (Bergemann)  
O, Mg, Si, Ca, Ti, Cr, Mn, Fe, Co
- [spectrum.inasan.ru/nLTE](http://spectrum.inasan.ru/nLTE) (Mashonkina)  
Ca, Ti, Fe
  
- pySME: [sme.astro.uu.se](http://sme.astro.uu.se) (Piskunov / Amarsi)  
Li, C, N, O, Na, Mg, Al, Si, Ca, Ti, Fe, Ba

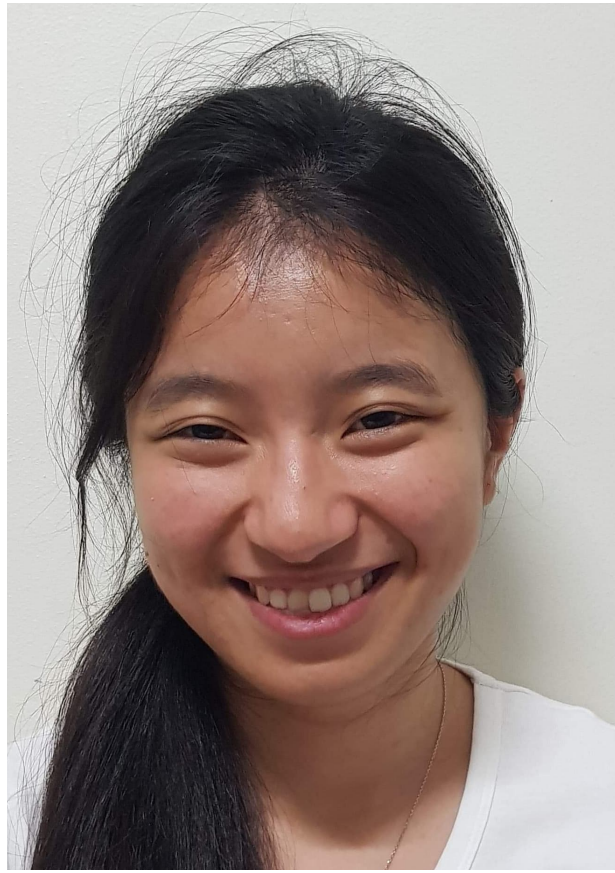
## 3D molecular lines:

- Collet, Asplund+ 2007
- Dobrovolskas, Kučinskas+ 2013
- Gallagher, Caffau+ 2016/2017

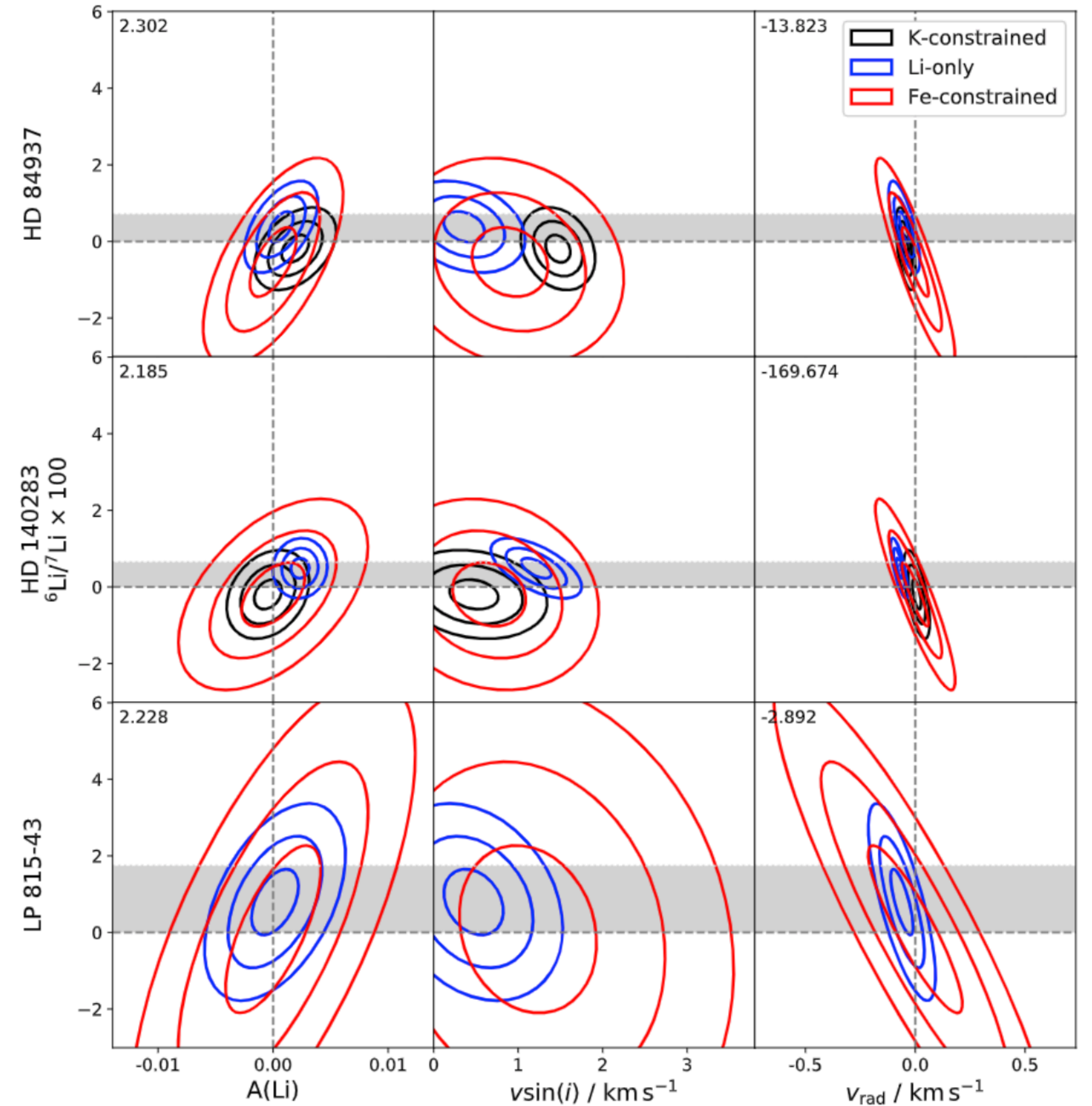
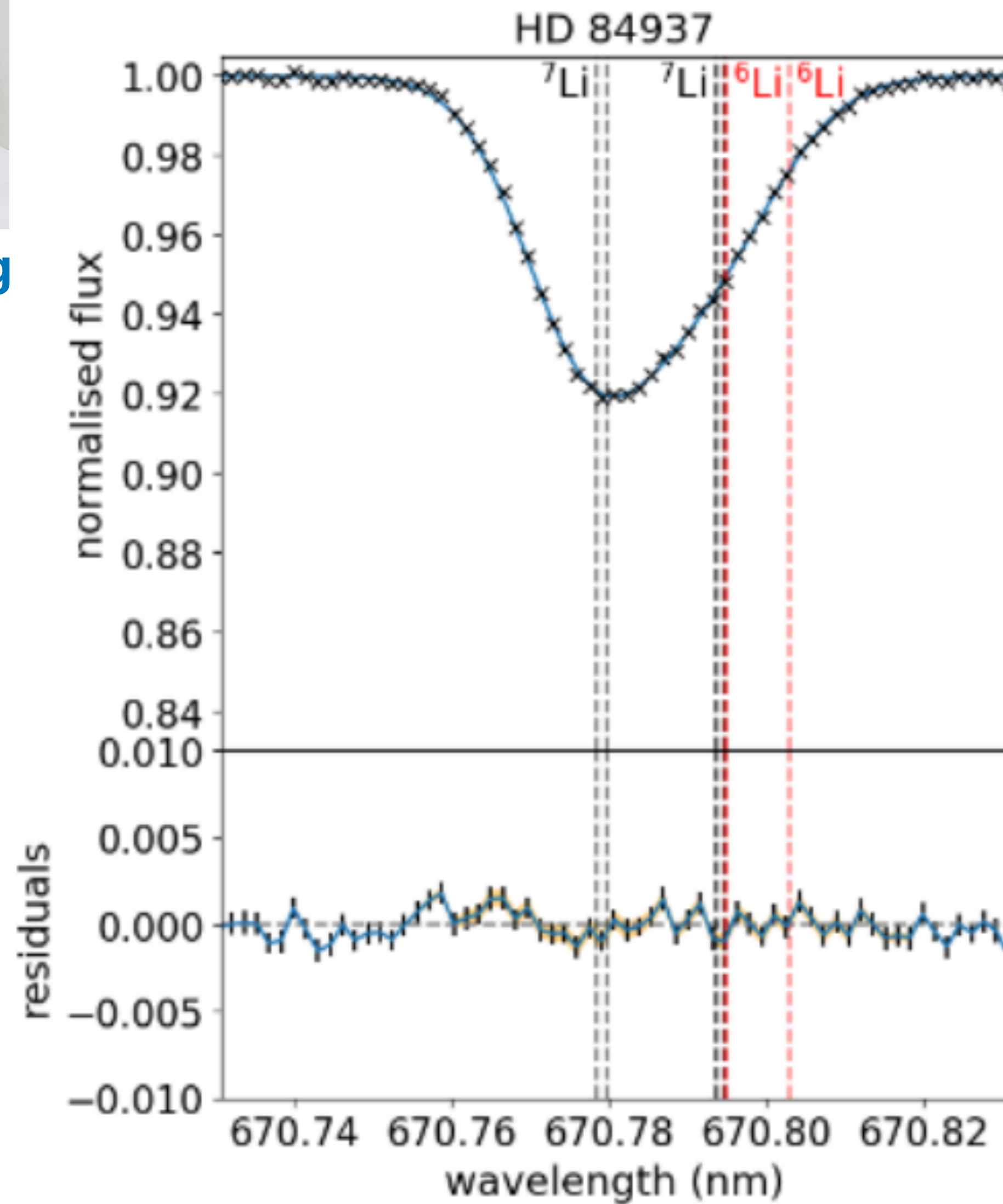




# Isotopic splitting

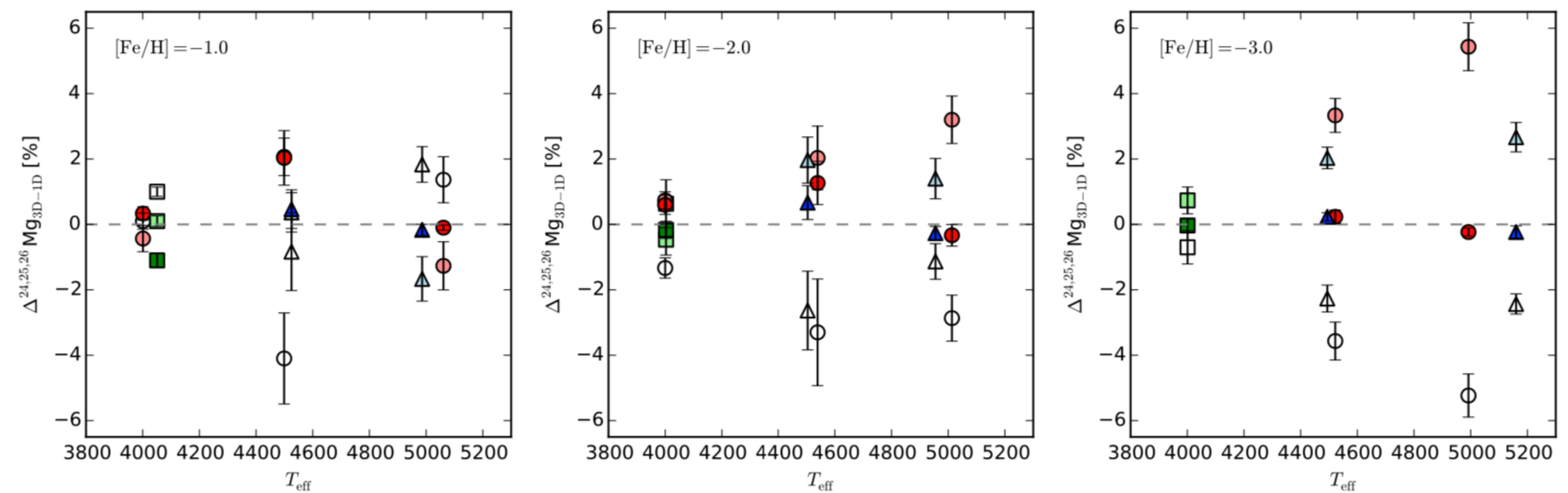
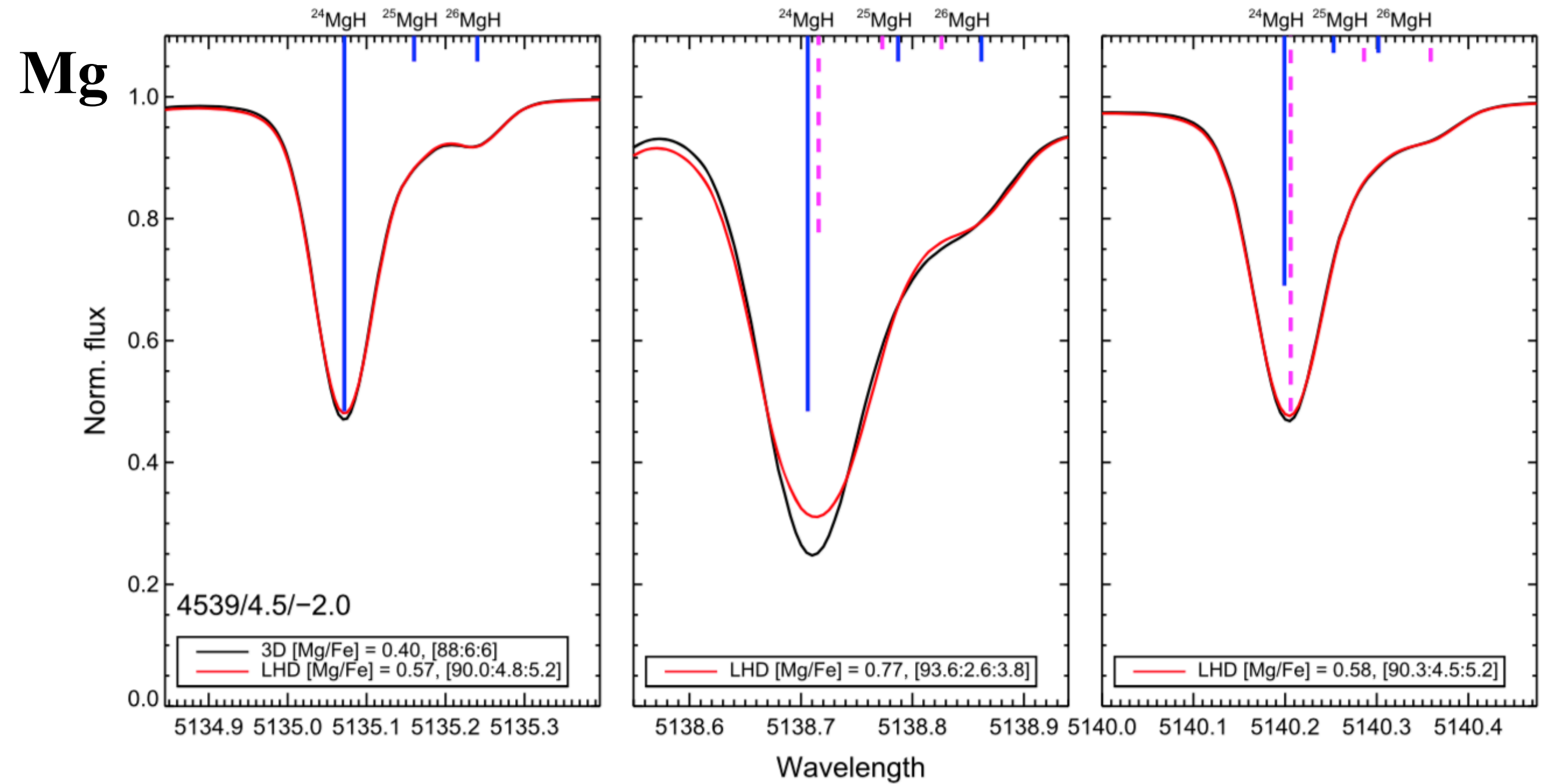
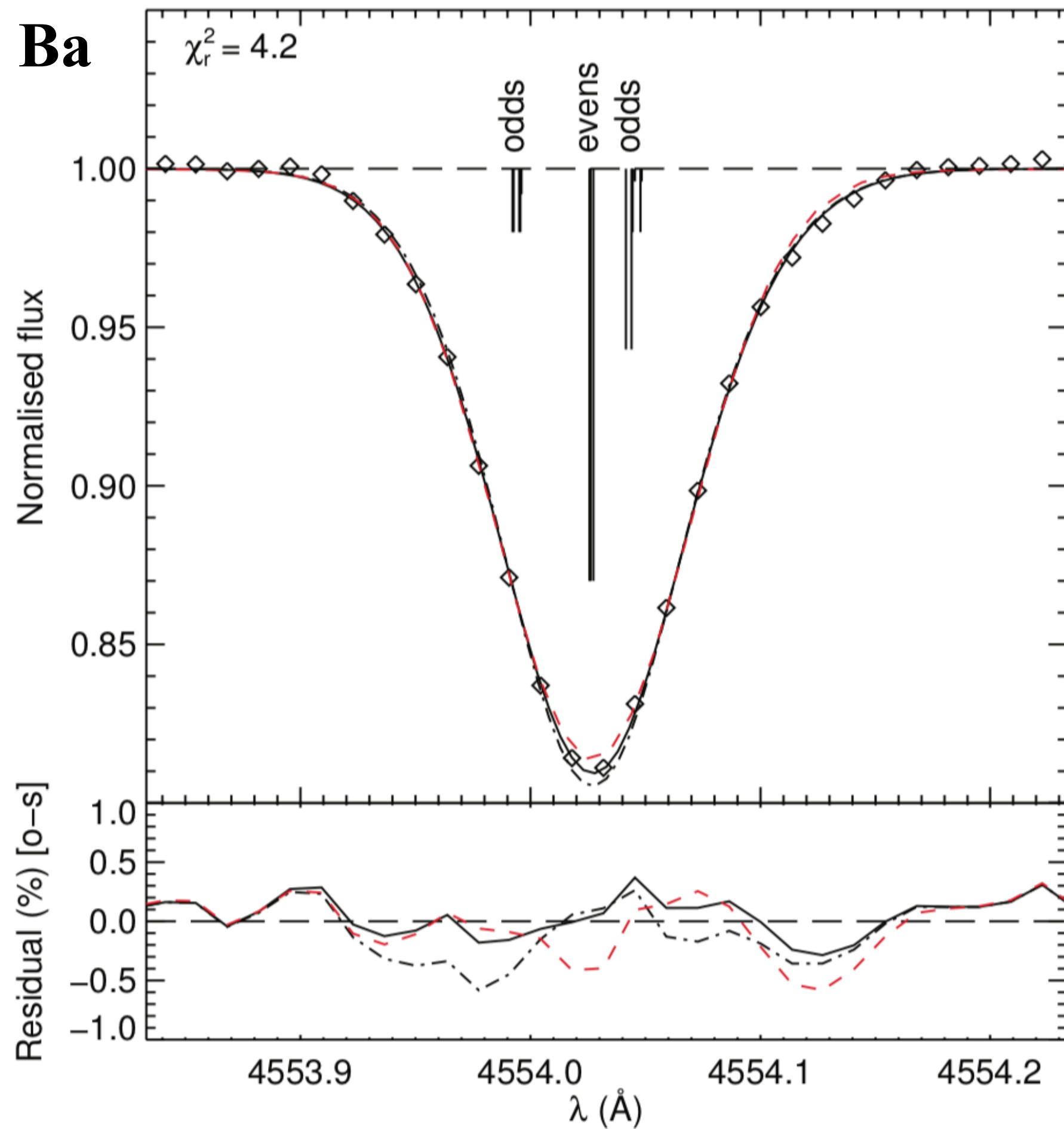


Ella (Xi) Wang





# Isotopic splitting



HD 140283

Gallagher, Ludwig+ 2015

Thygesen, Kirby+ 2017

# 3D effects on molecular lines

