New light on metal-poor stars

Thomas Nordlander
Australian National University - Mount Stromlo

thomasn@mso.anu.edu.au

ASTRO 3D

ARC CENTRE OF EXCELLENCE FOR ALL SKY ASTROPHYSICS IN 3D

Stellar spectroscopy

Stellar parameters
T_{eff}, $\log(g)$, [Fe/H], [X/Fe], …

Radiative transfer

Physical assumptions
1D+MLT, LTE, opacities, ...

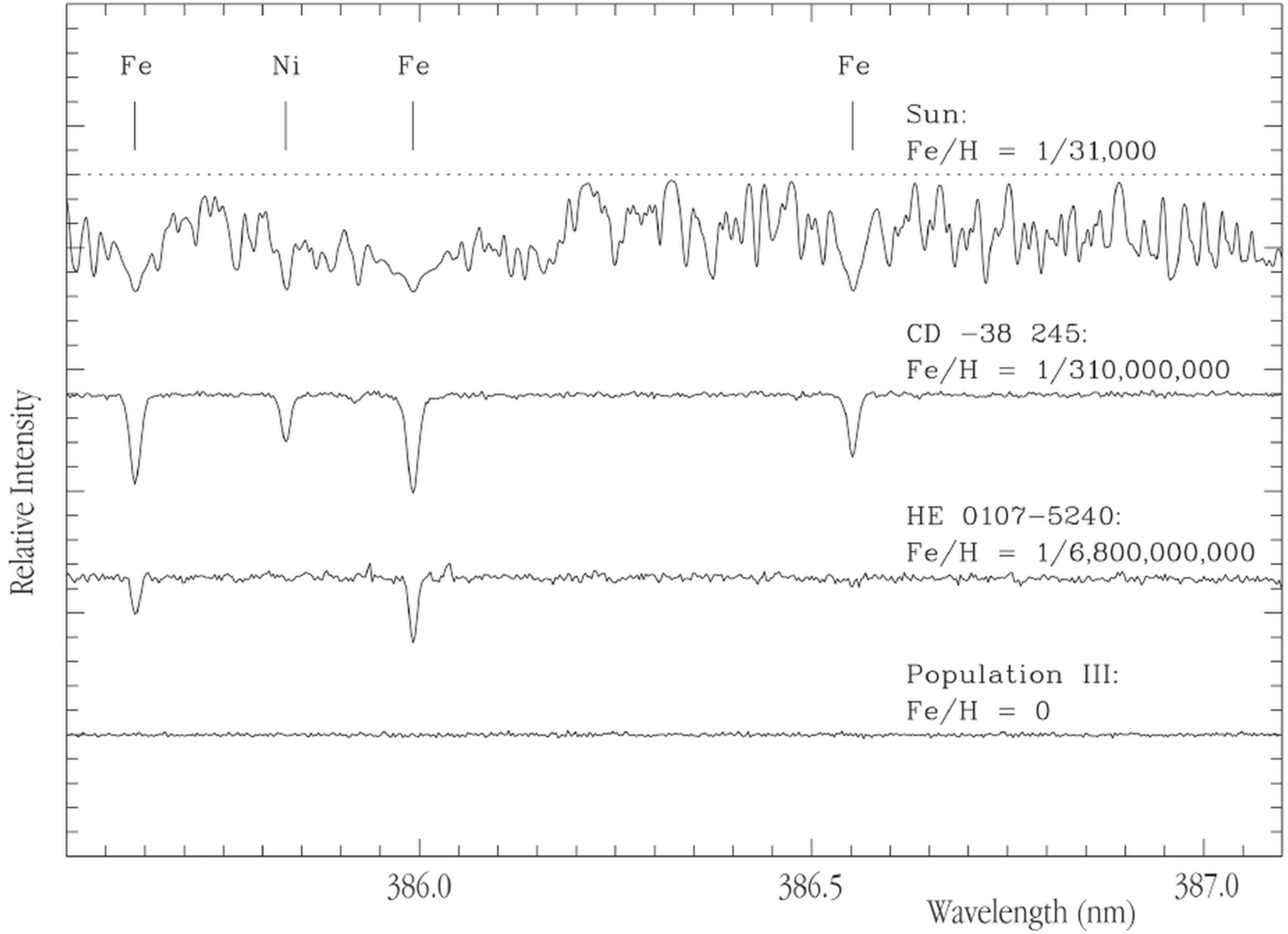


Image credit: Christlieb/ESO

Stellar atmospheres

$$\mathscr{F}_{\rm tot} = \mathscr{F}_{\rm rad} + \mathscr{F}_{\rm conv}$$

$$\mathscr{F}_{\rm rad} = \int F(\lambda)\, \mathrm{d}\,\lambda$$

$$\mathscr{F}_{\rm conv} \propto \alpha_{\rm MLT}\,(\nabla_T - \nabla_{\rm ad})$$

$$\alpha_{\rm MLT} = \frac{l}{H_p} \qquad \nabla_T = \frac{\mathrm{d}\ln T}{\mathrm{d}\ln P}$$

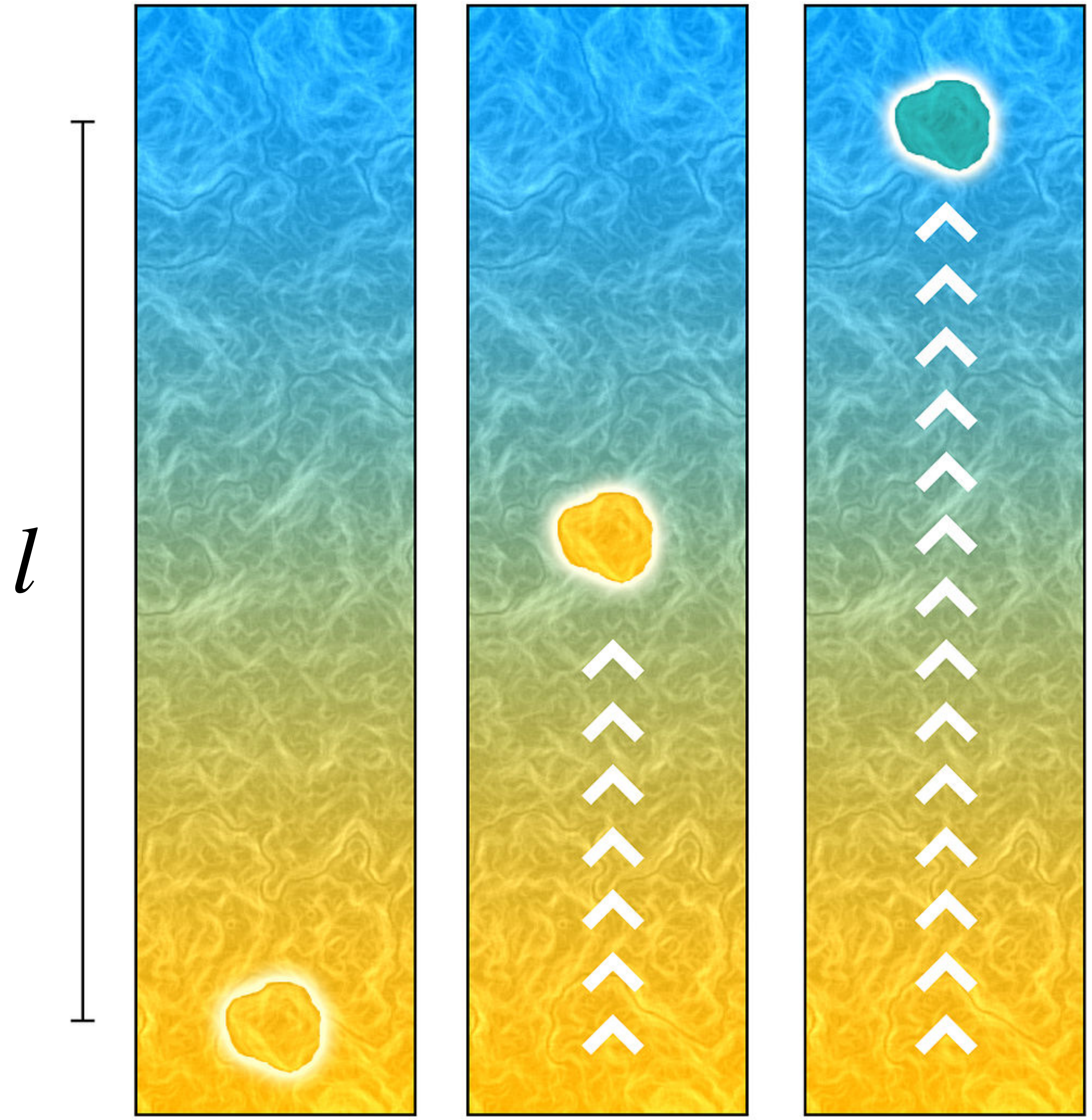
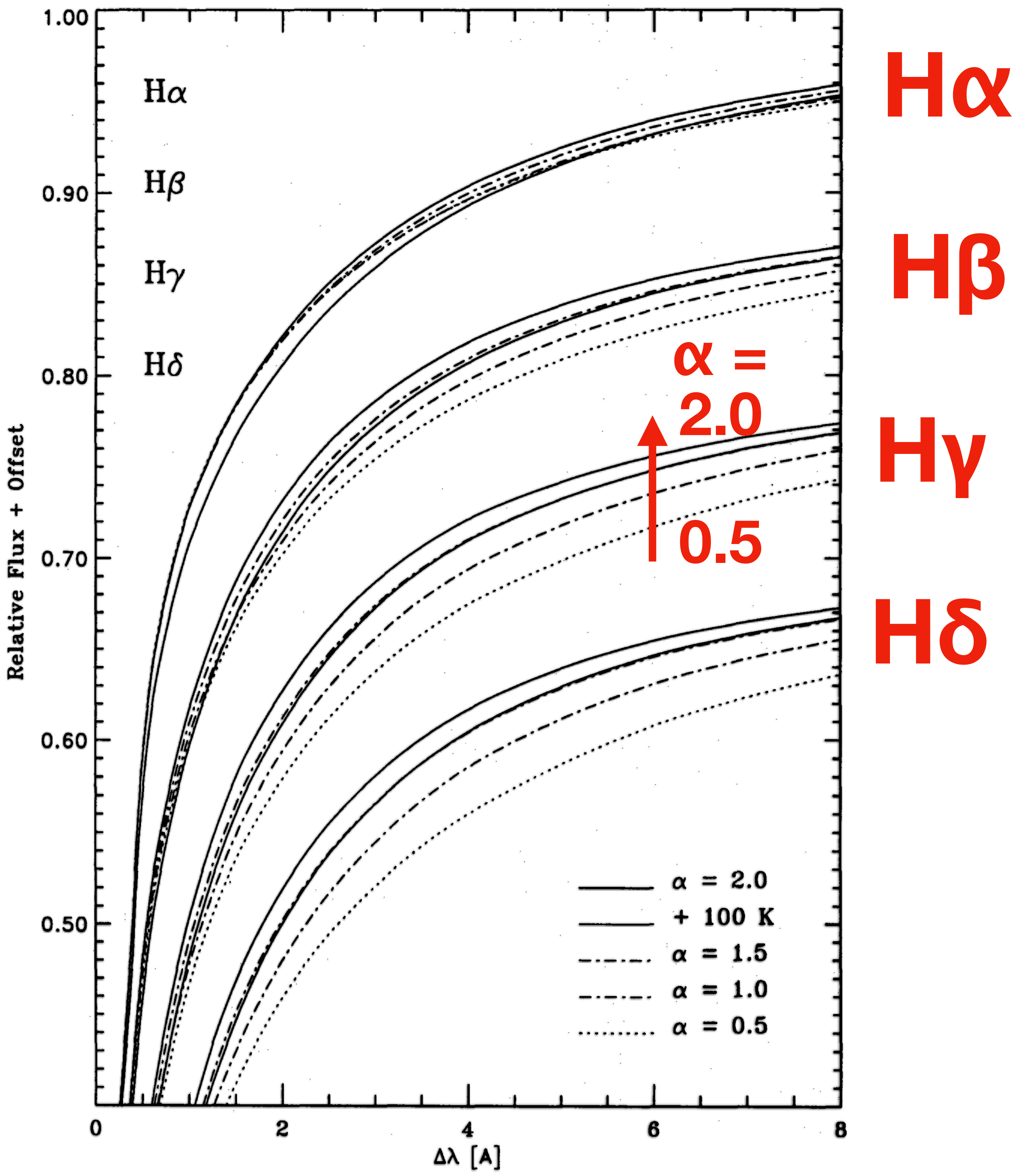
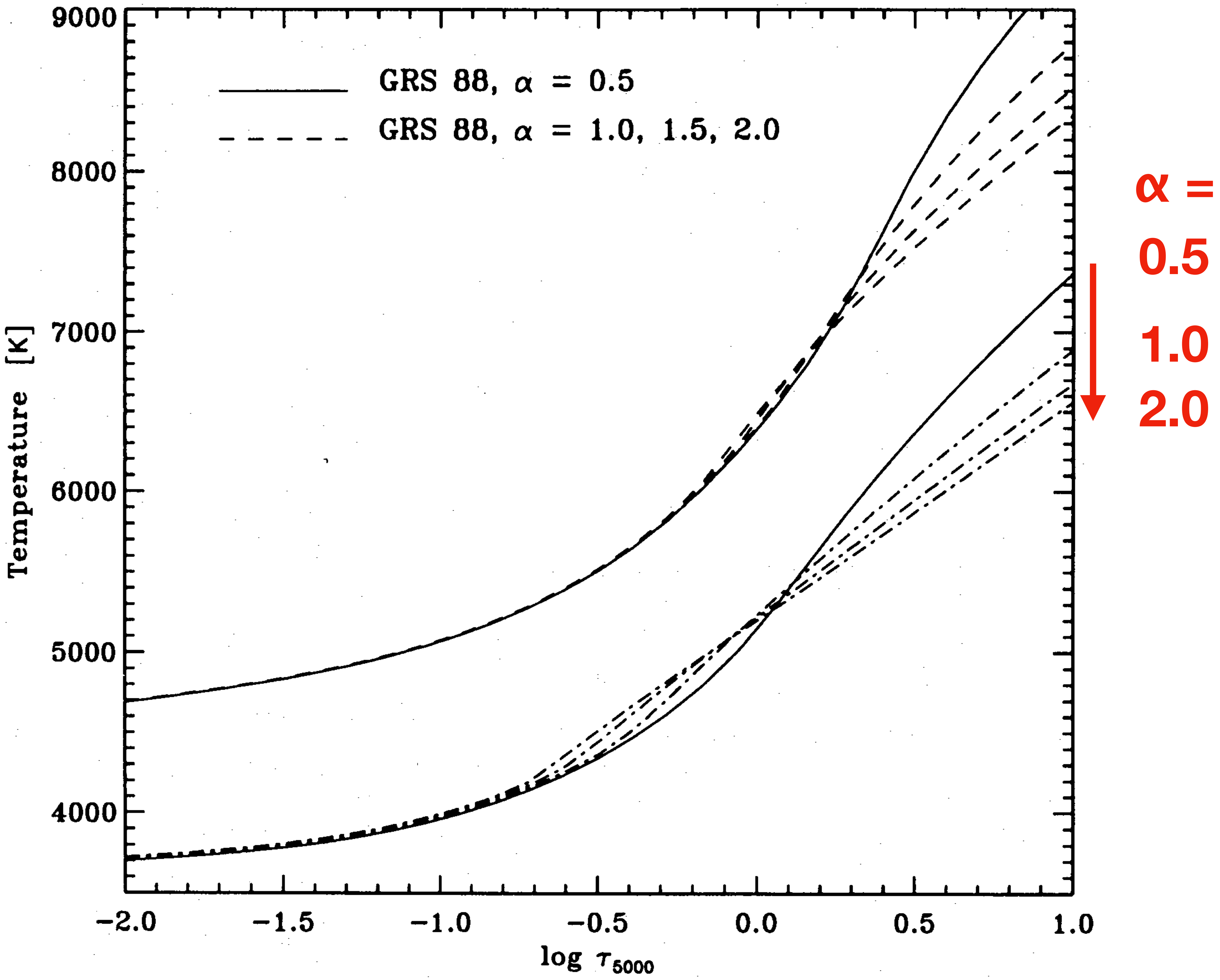


Image credit: Nedtheprotist/Wikipedia

MLT from spectroscopy: α ~ 0.5





Fuhrmann, Axer, Gehren 1993

MLT from stellar evolution: α ~ 2

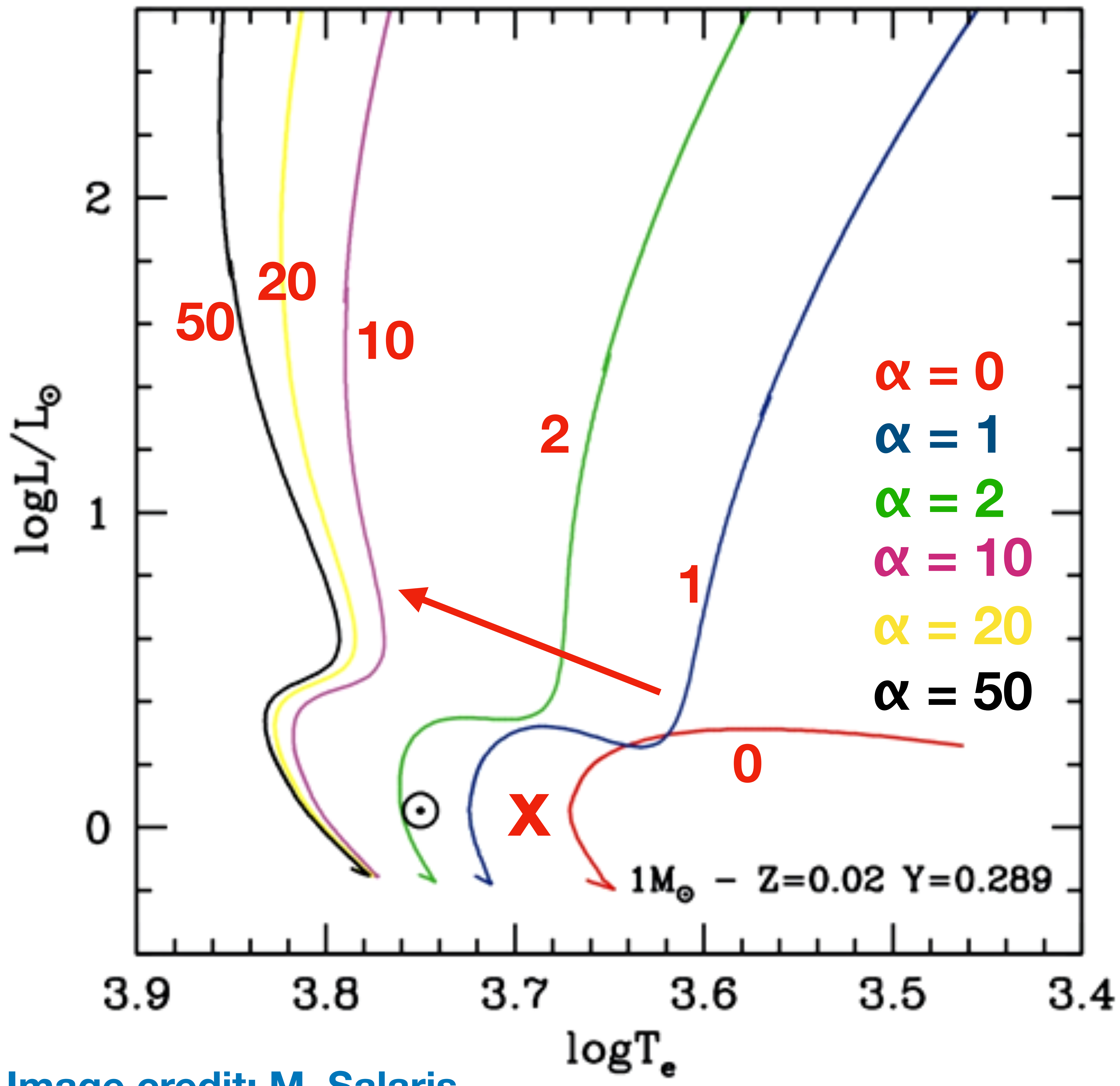
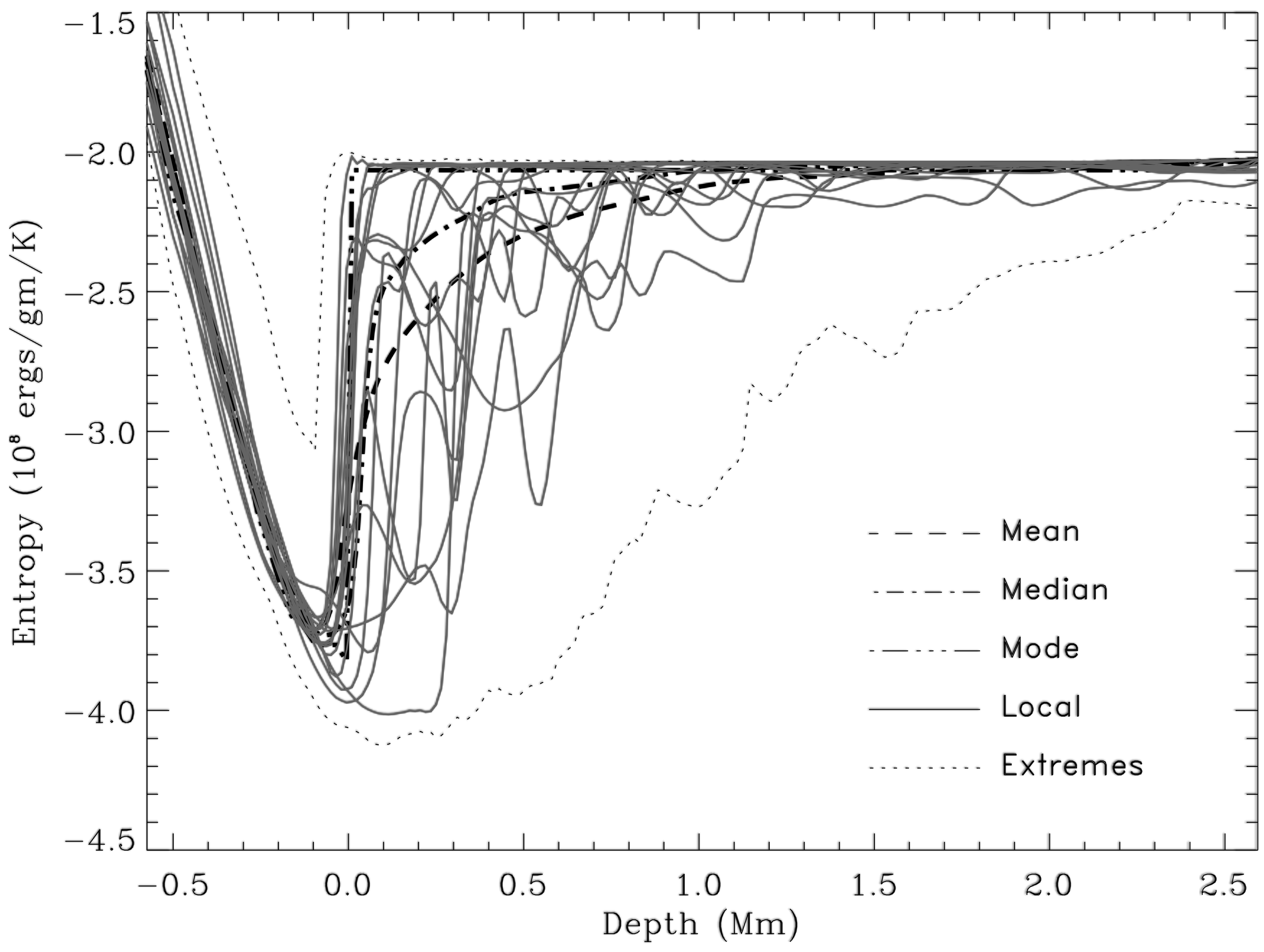


Image credit: M. Salaris

Code	Solar Z/X	α
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^2	0.0253	1.743
PARSEC	0.0252	1.740
Padova	0.0235	1.680
Geneva	0.0194	1.647

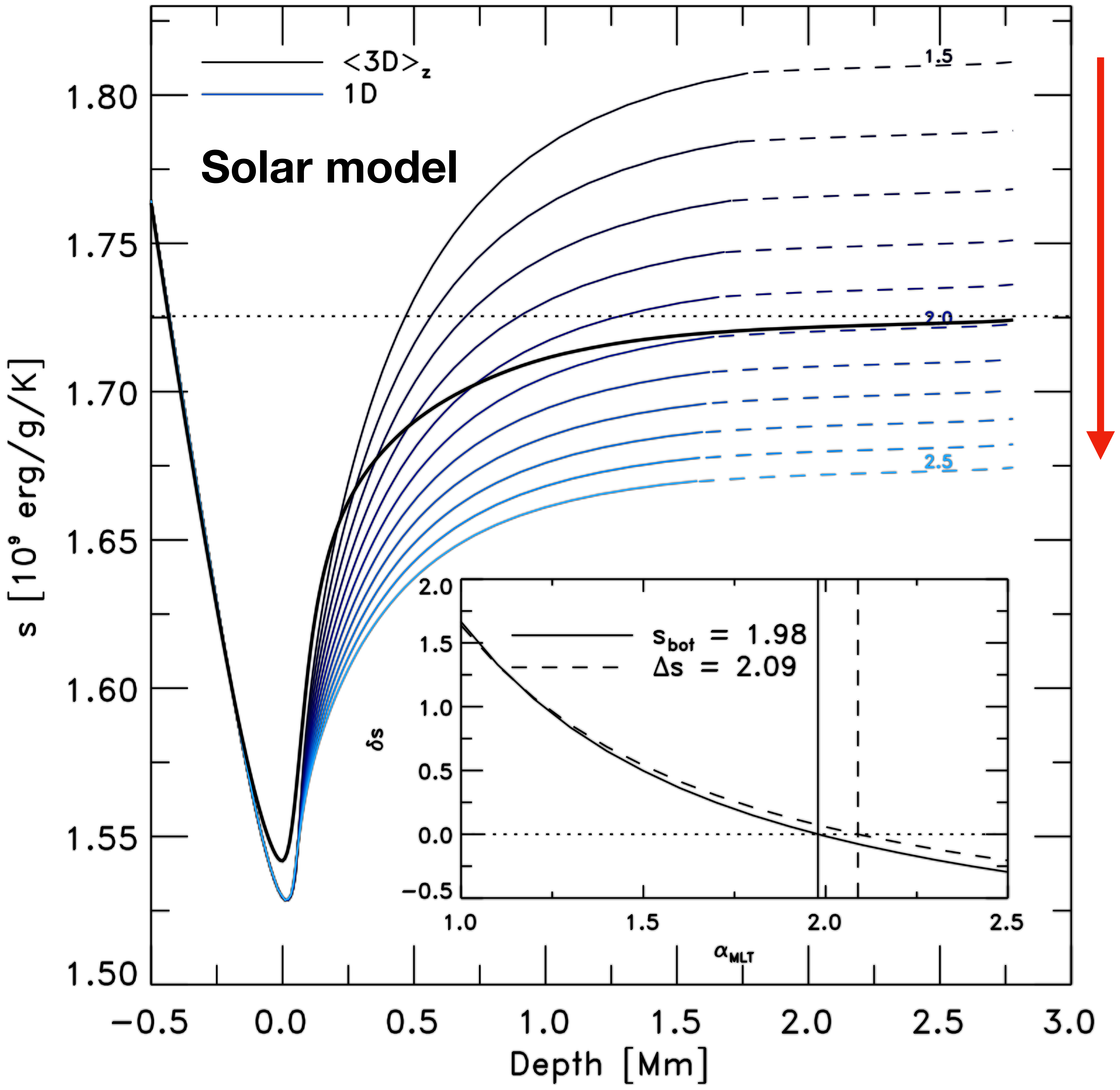
Stancliffe, Fossati, Passy+ 2016

MLT from 3D simulations: α ~ 2



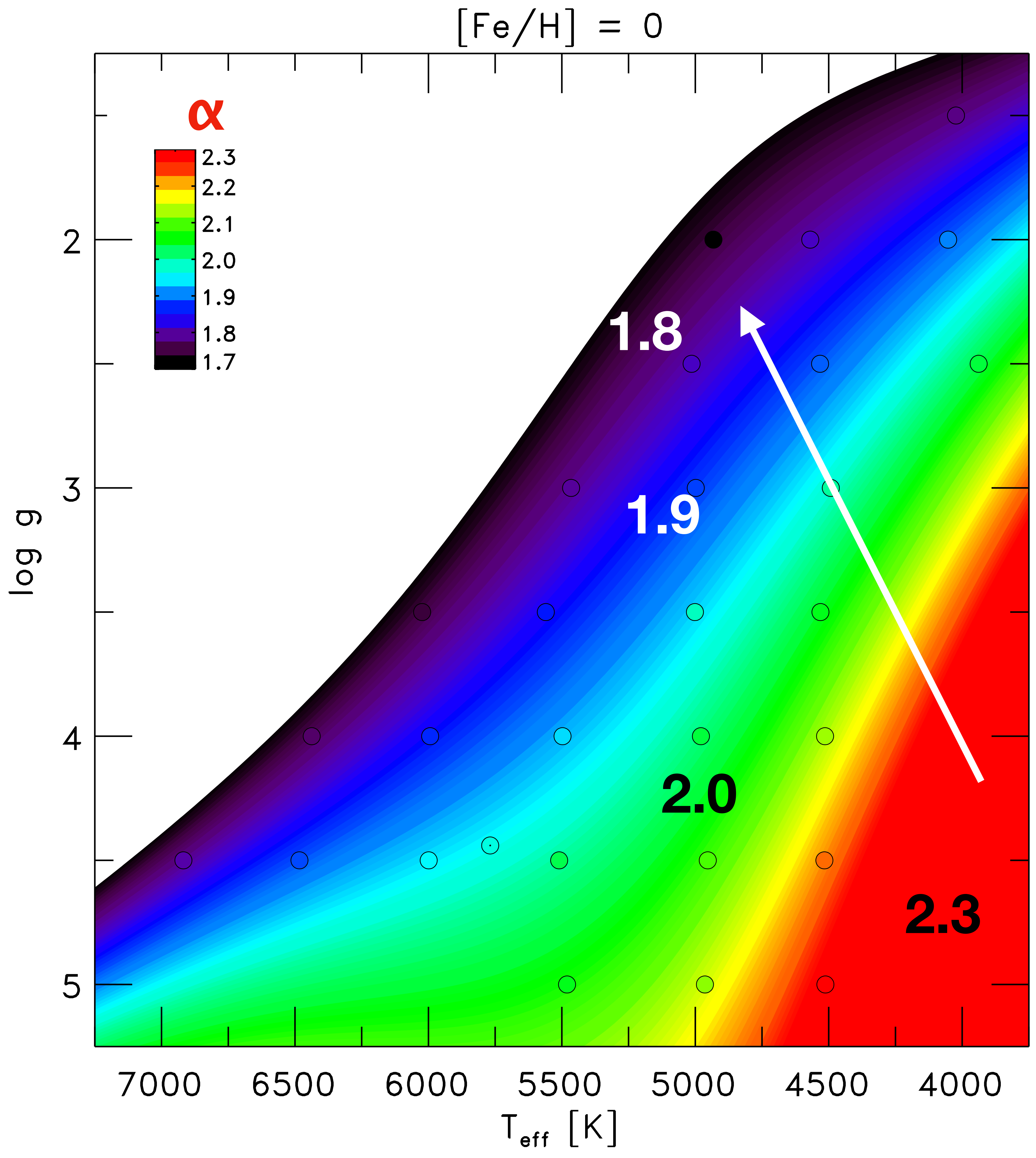
Stein & Nordlund 1998

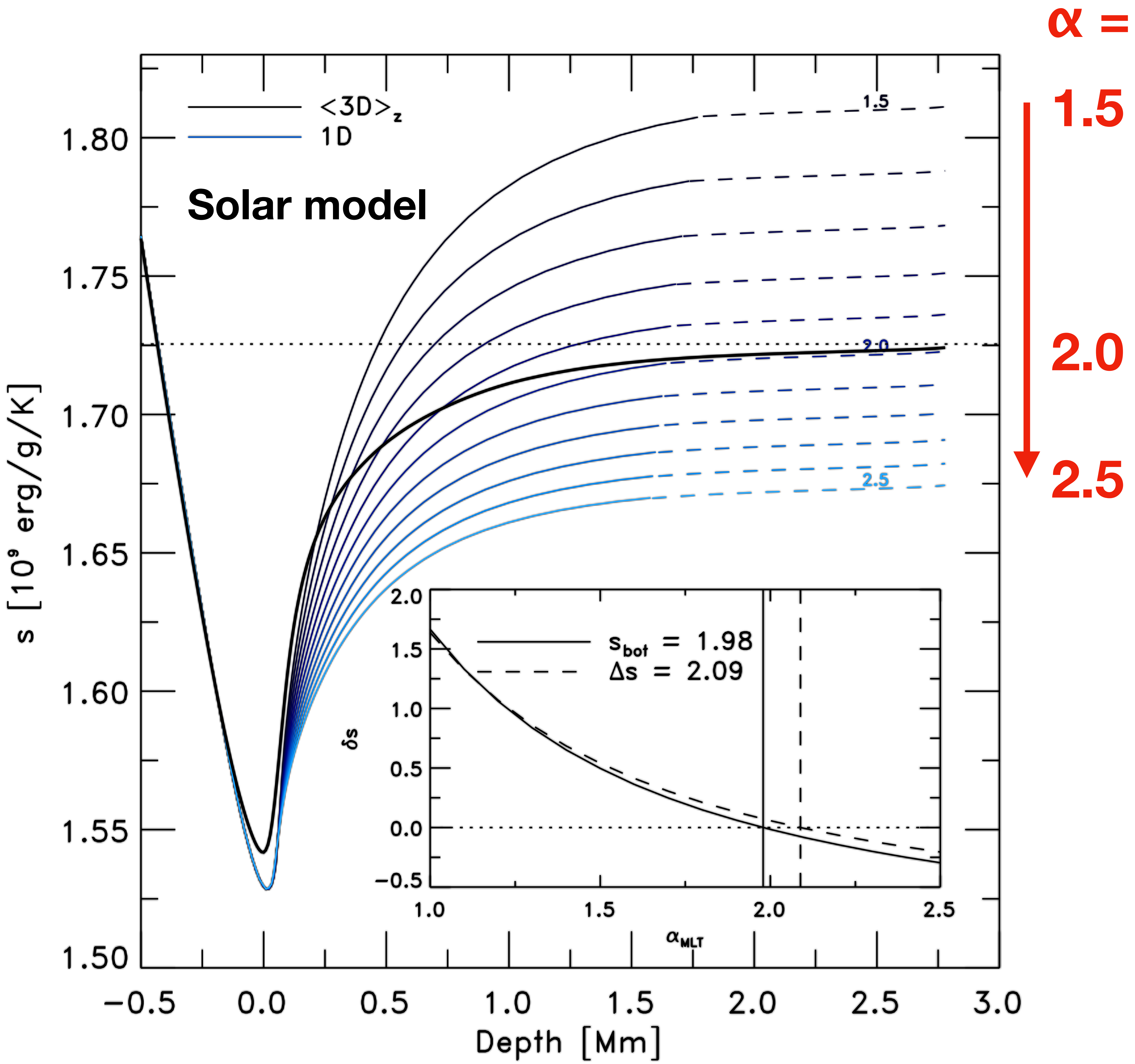
α =



Magic, Weiss, Asplund 2015

MLT from 3D simulations: α ~ 2





Magic, Weiss, Asplund 2015

Non-LTE = Statistical equilibrium

$$0 = \frac{\mathrm{d}\boxed{n_i}}{dt} = \boxed{\sum_{j \neq i} n_j \left(R_{ji} + C_{ji}\right)} - \boxed{n_i \sum_{j \neq i} \left(R_{ij} + C_{ij}\right)}$$

Particle number

Incoming transitions

Outgoing transitions

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

Collisional transitions: C_{ij}

Radiation field is non-local!

Non-LTE = Statistical equilibrium

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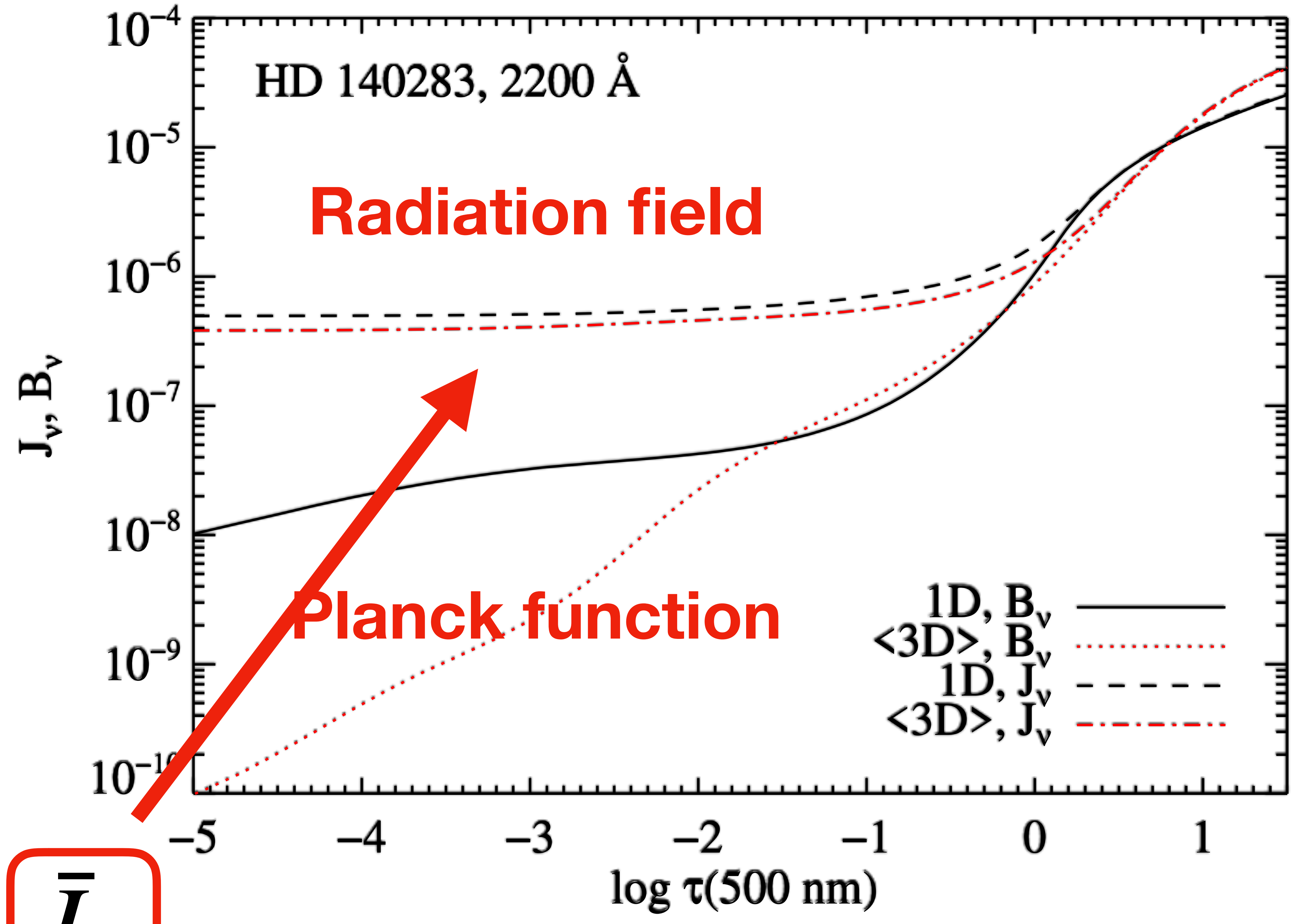
Particle number

Incoming transitions



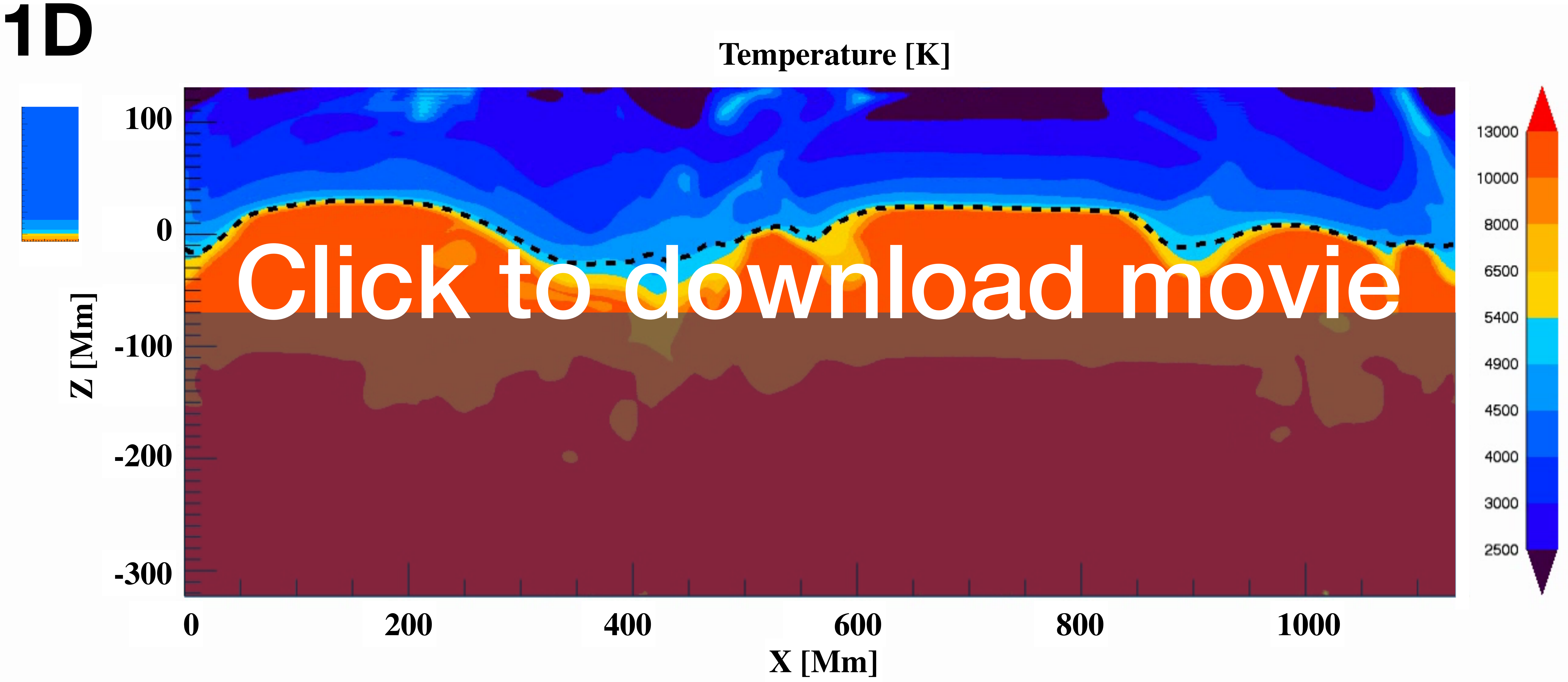
Radiative transitions: $R_{ij} = A_{ij} + B_{ij} \boxed{\bar{J}_\nu}$

Collisional transitions: C_{ij}

Radiation field is non-local!

Bergemann, Lind, Collet+ 2012

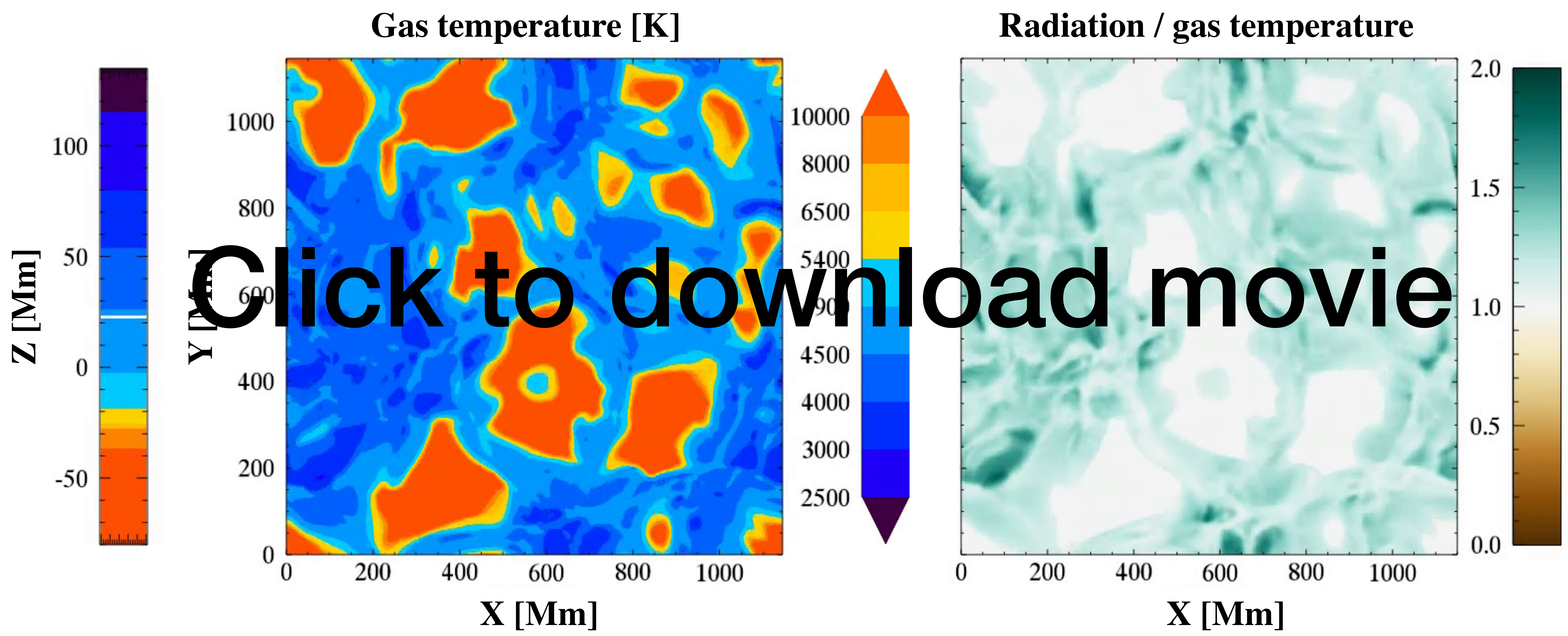
3D RHD model atmospheres



See also Magic, Collet, Asplund+ 2013-2015

TN, Amarsi, Lind+ 2017

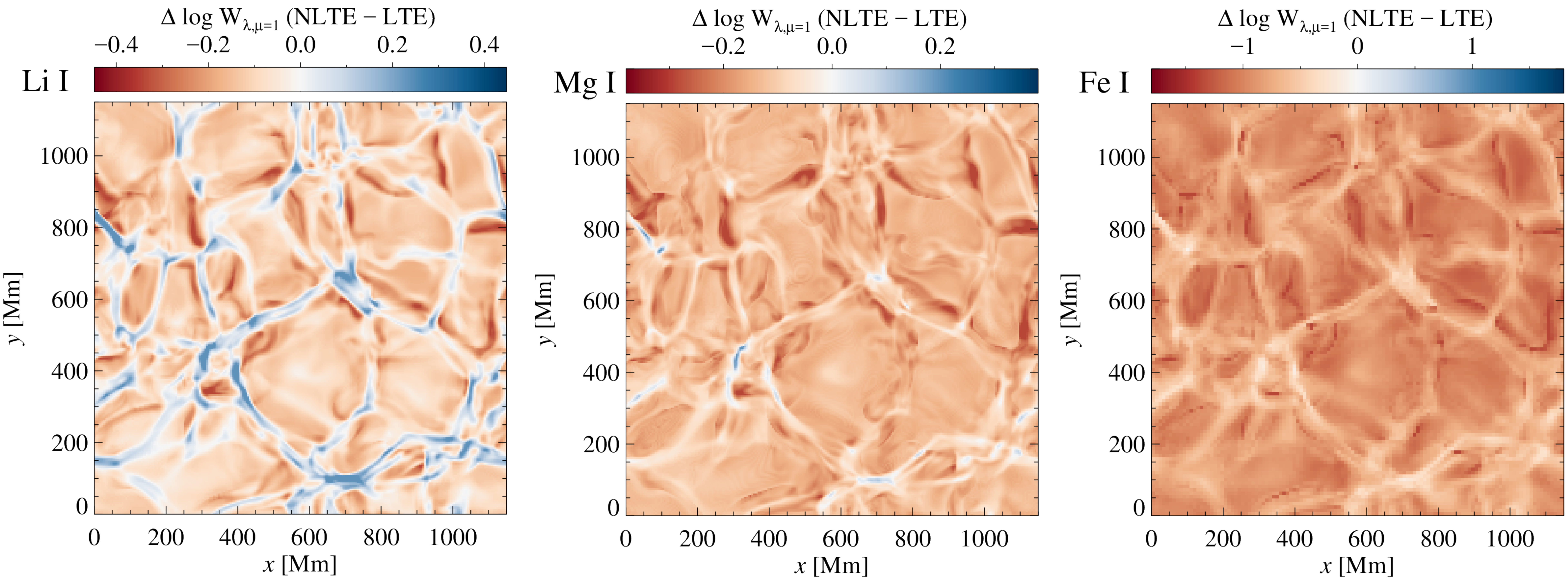
Non-LTE in 3D



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

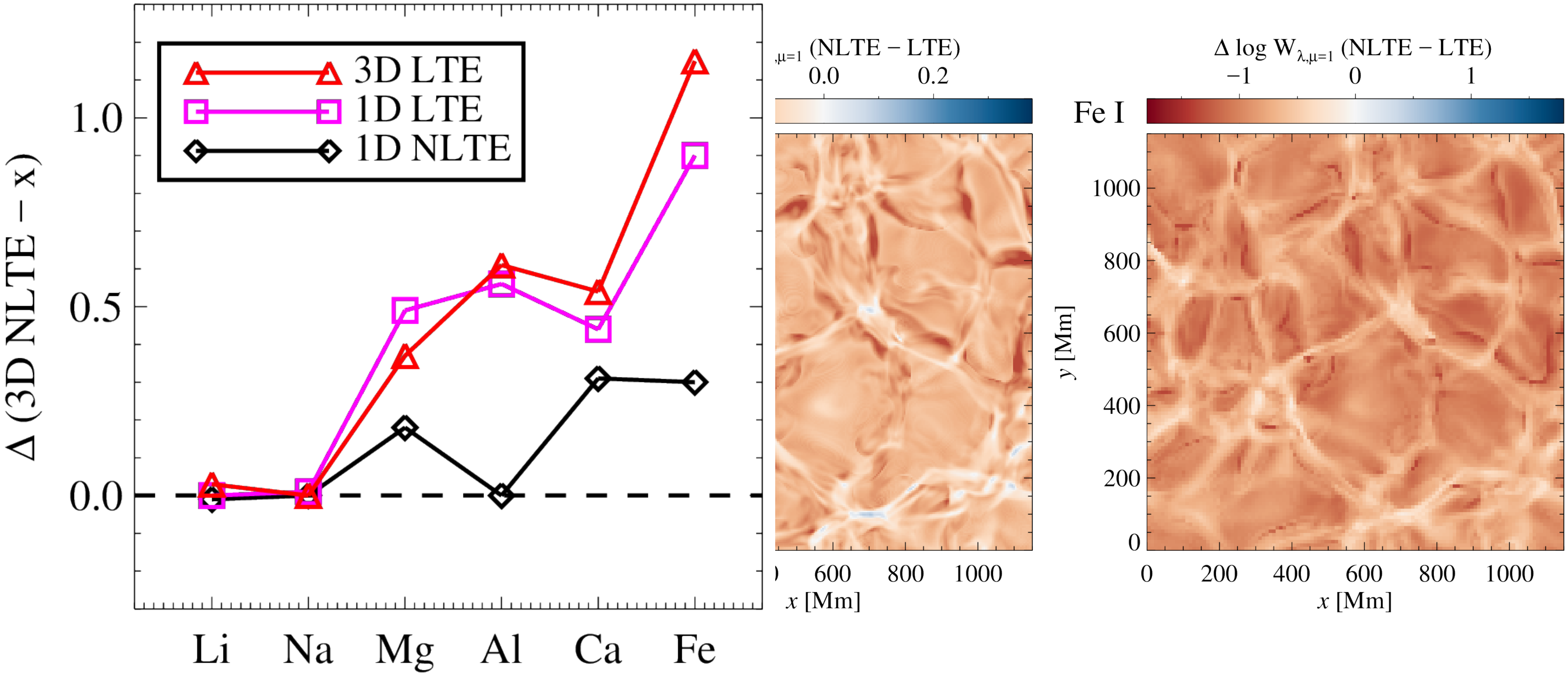
TN, Amarsi, Lind+ 2017

SMSS 0313-6708 in 3D NLTE



TN, Amarsi, Lind+ 2017

SMSS 0313-6708 in 3D NLTE



TN, Amarsi, Lind+ 2017

Extremely metal-poor stars

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ASTRO 3D

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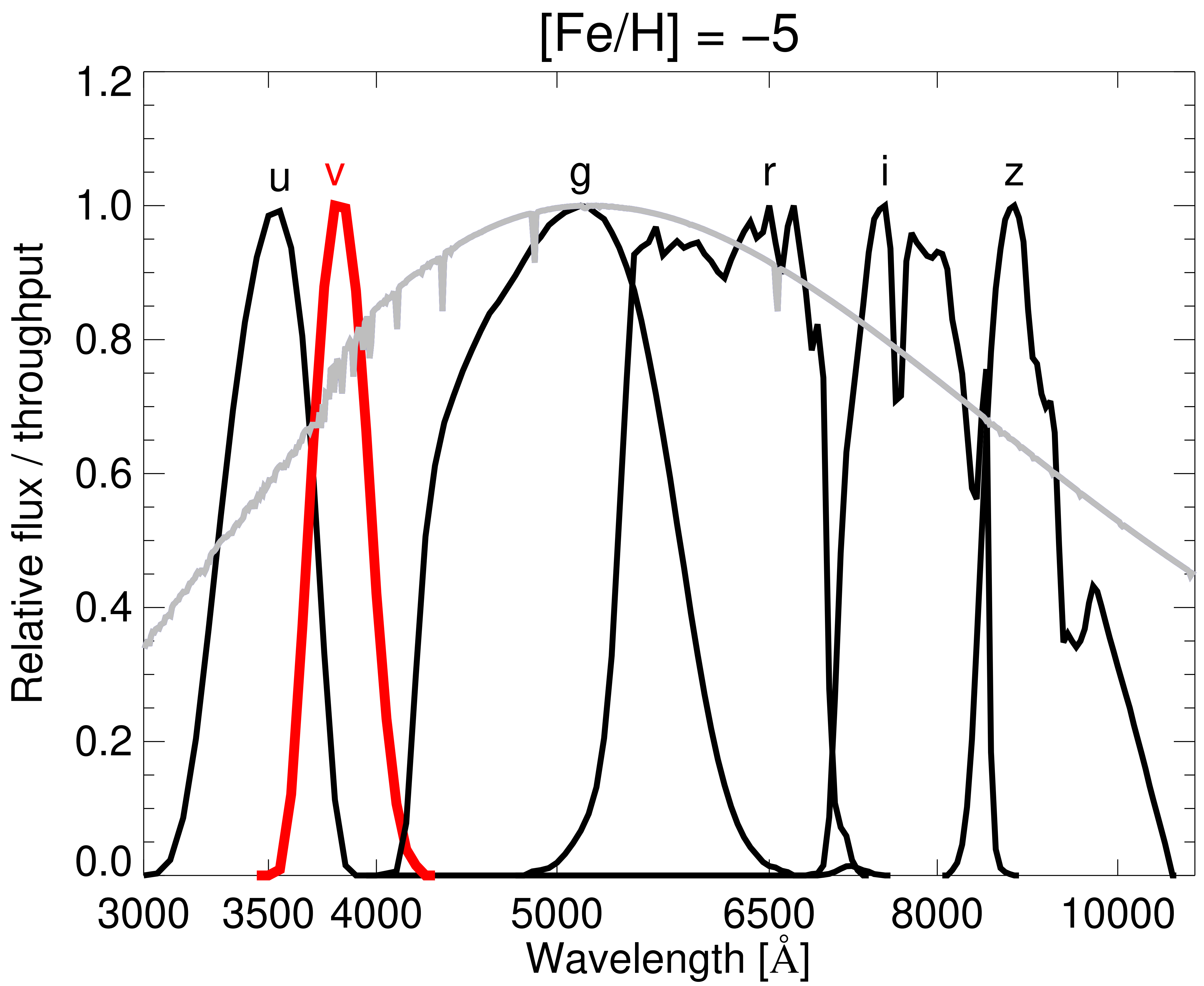
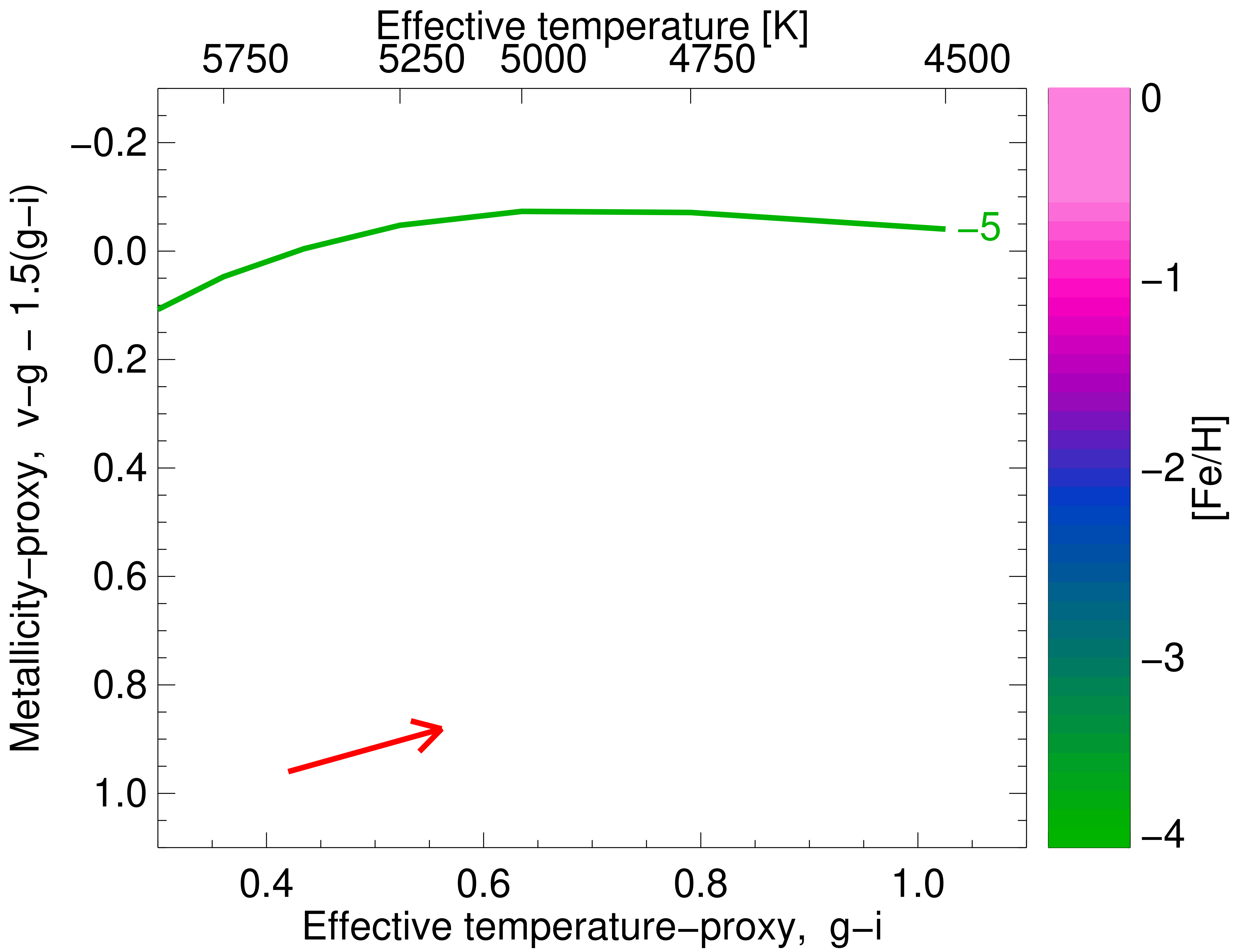
SkyMapper Extremely Metal-Poor Star Group

ANU: Martin Asplund, Michael Bessell, Gary Da Costa, Dougal Mackey, Anna Marino, TN, John Norris, Brian Schmidt
Monash: Andrew Casey, Alexander Heger; **MIT**: Anna Frebel; **MPIA**: Karin Lind; **UNSW/ADFA**: Simon Murphy

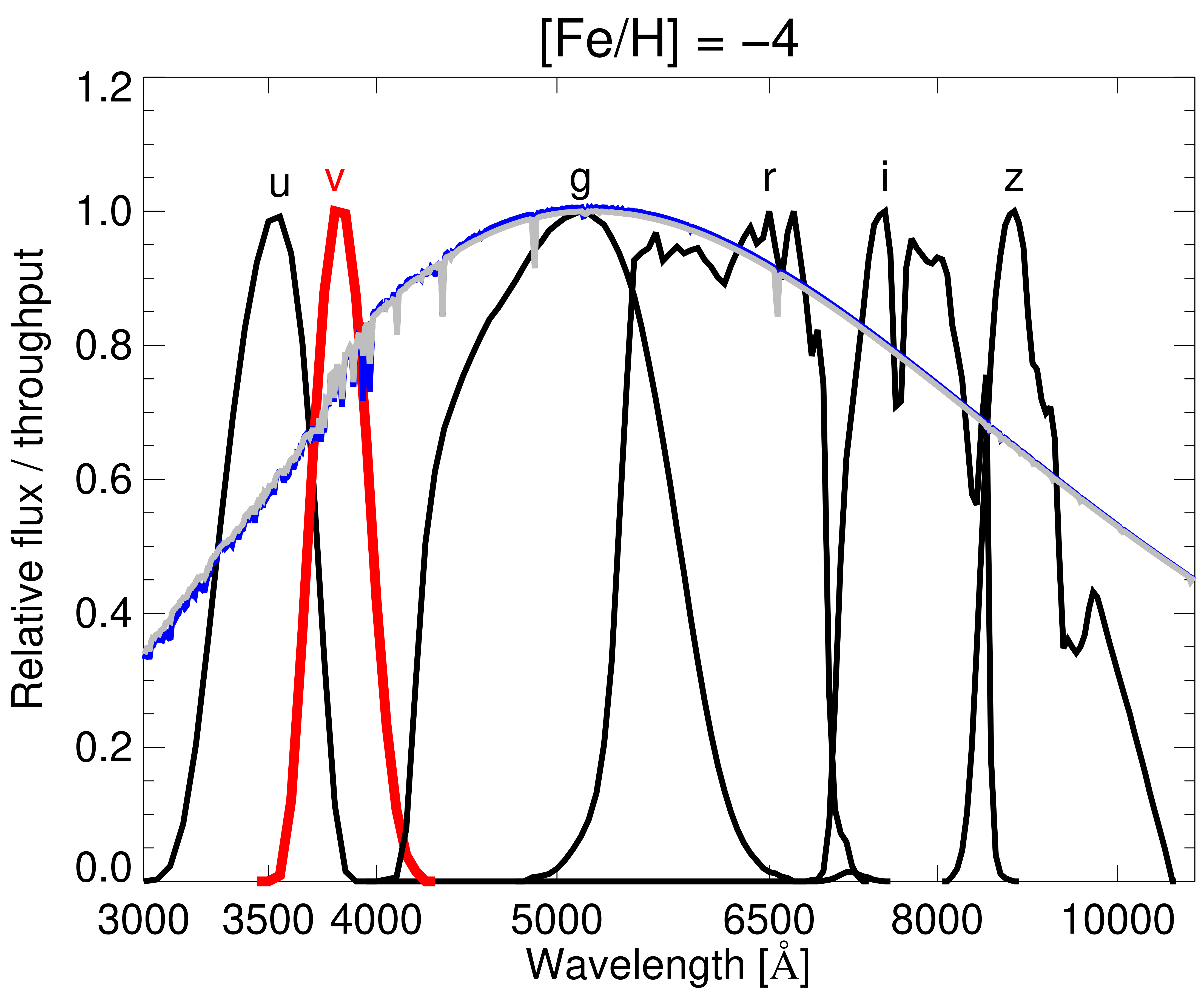
The SkyMapper EMP search

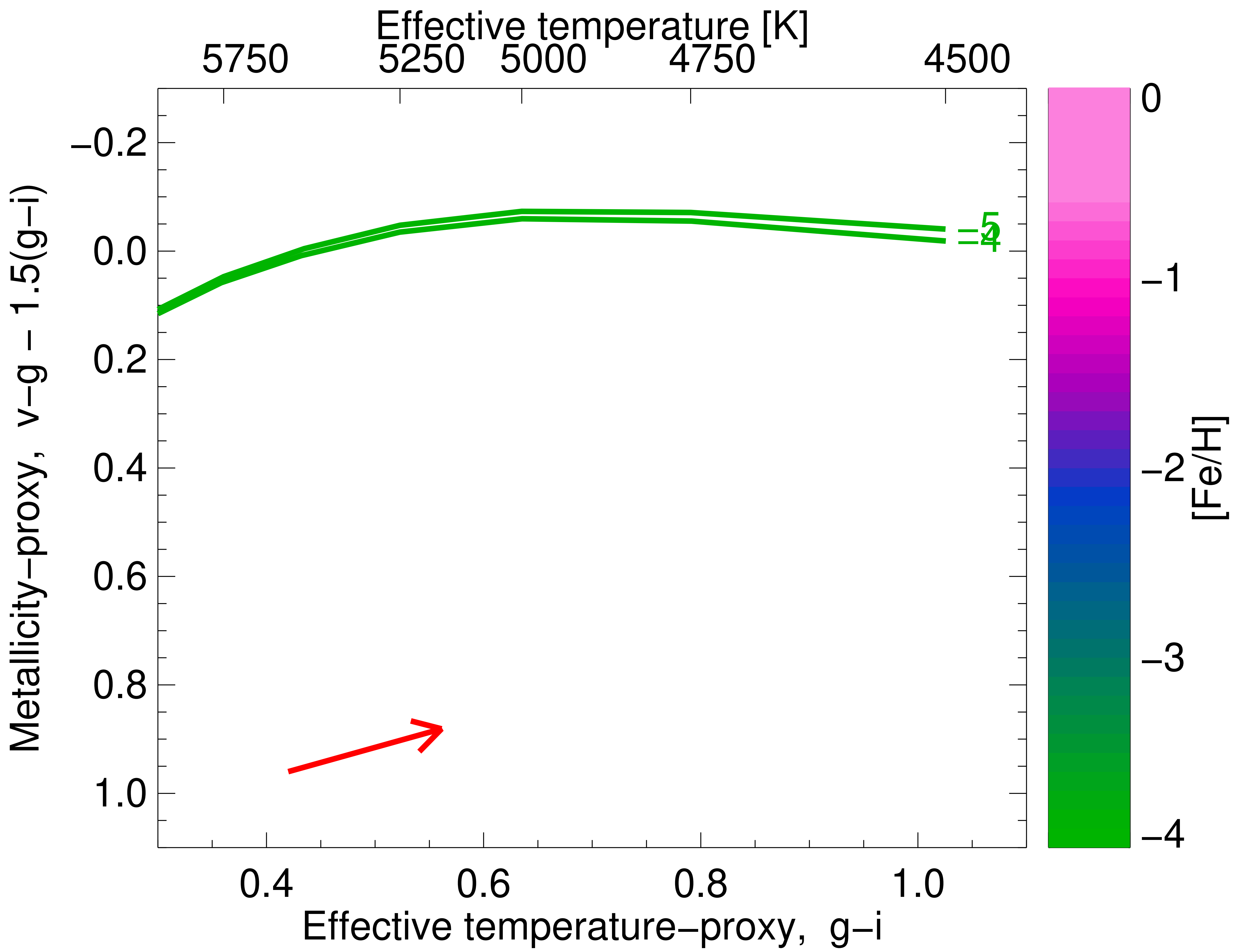




Da Costa, Bessell, Mackey, TN+ submitted

The SkyMapper EMP search





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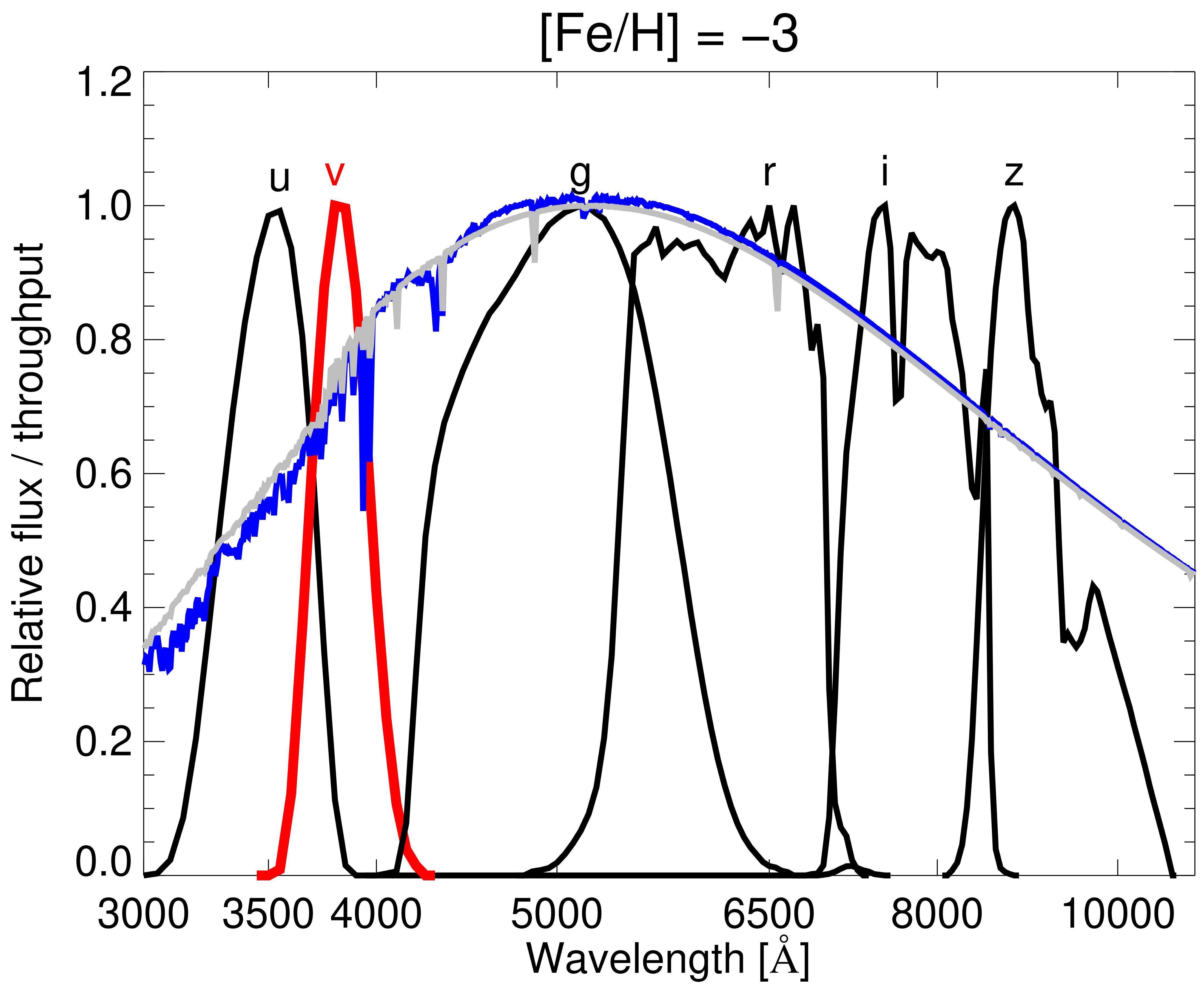

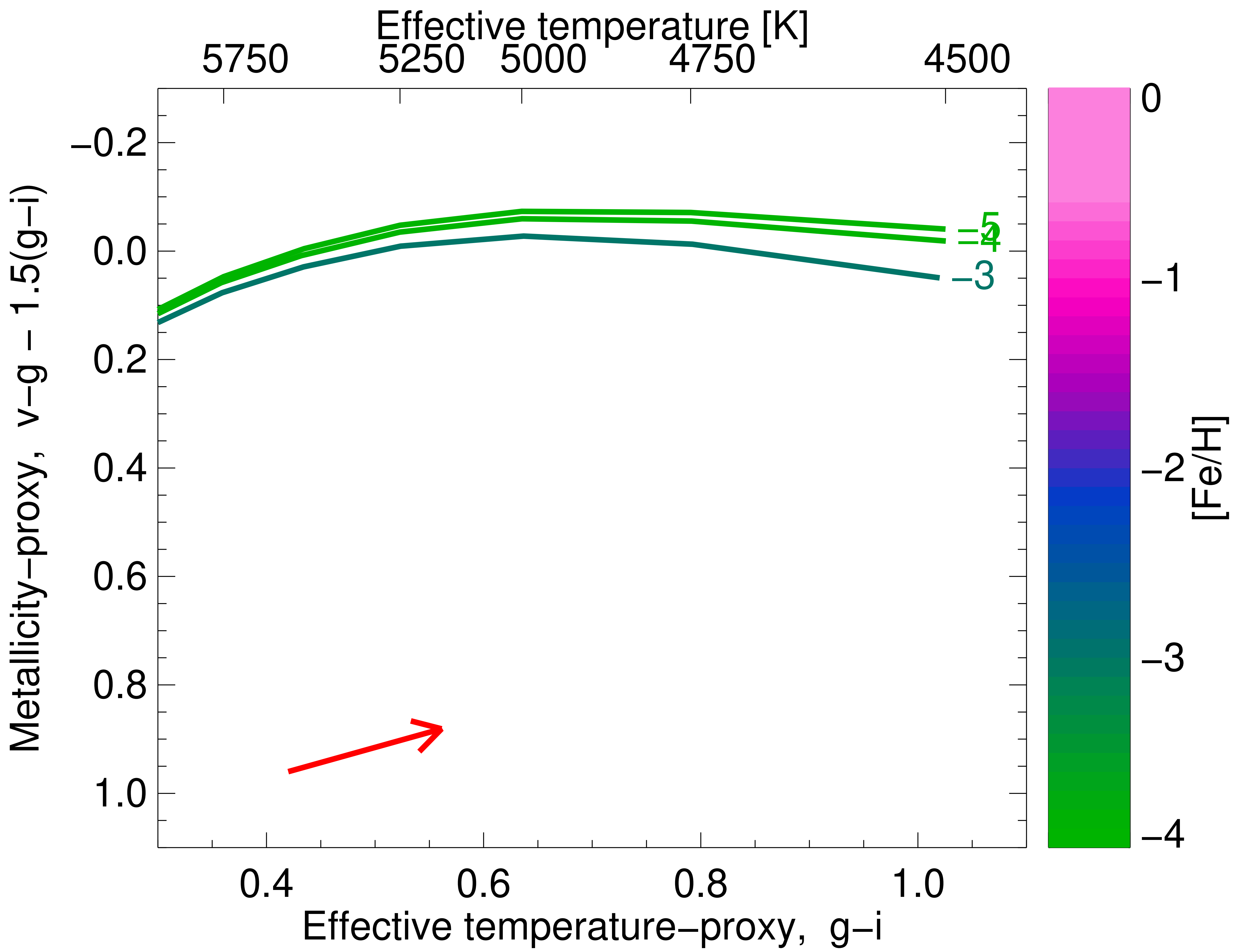

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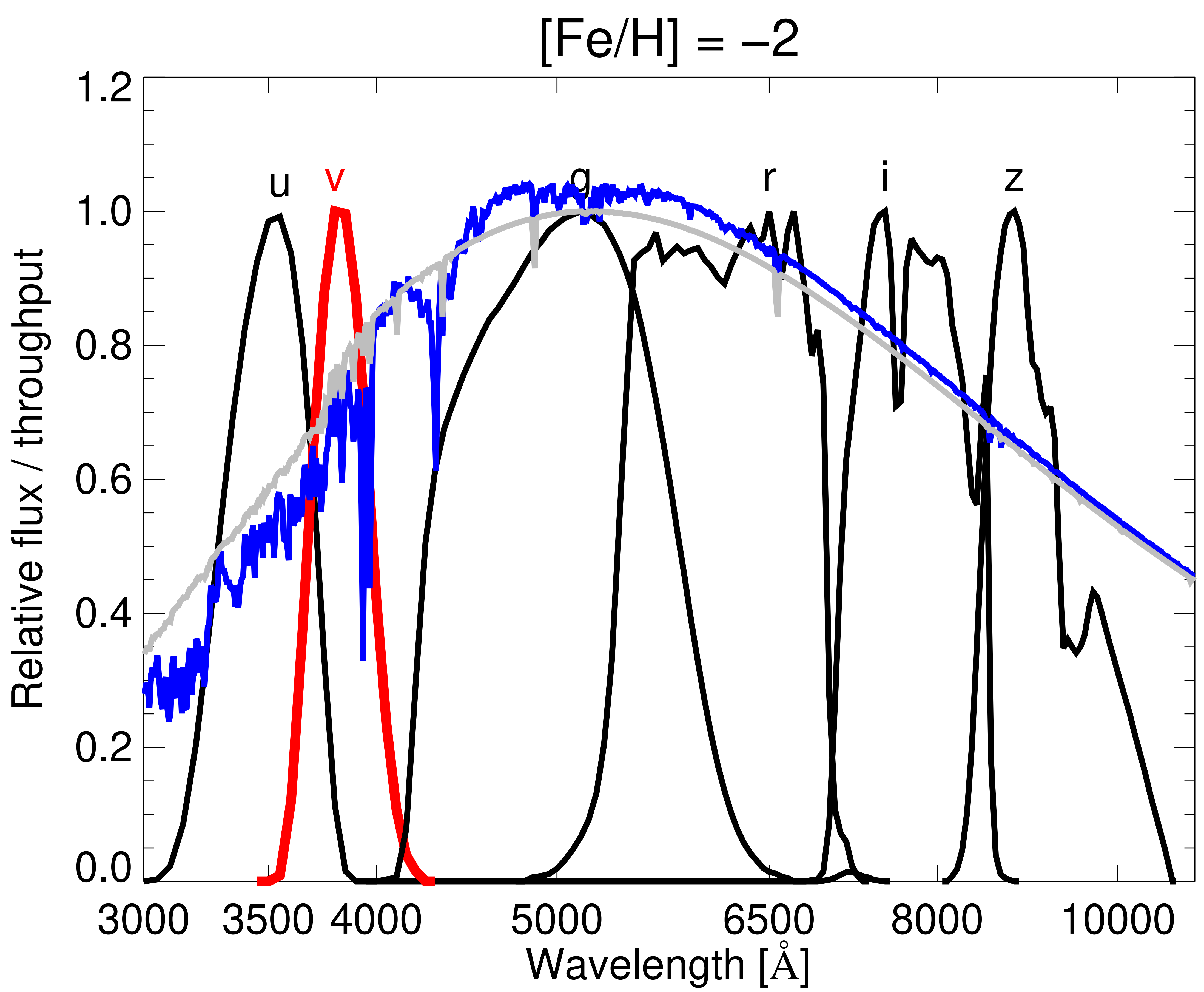

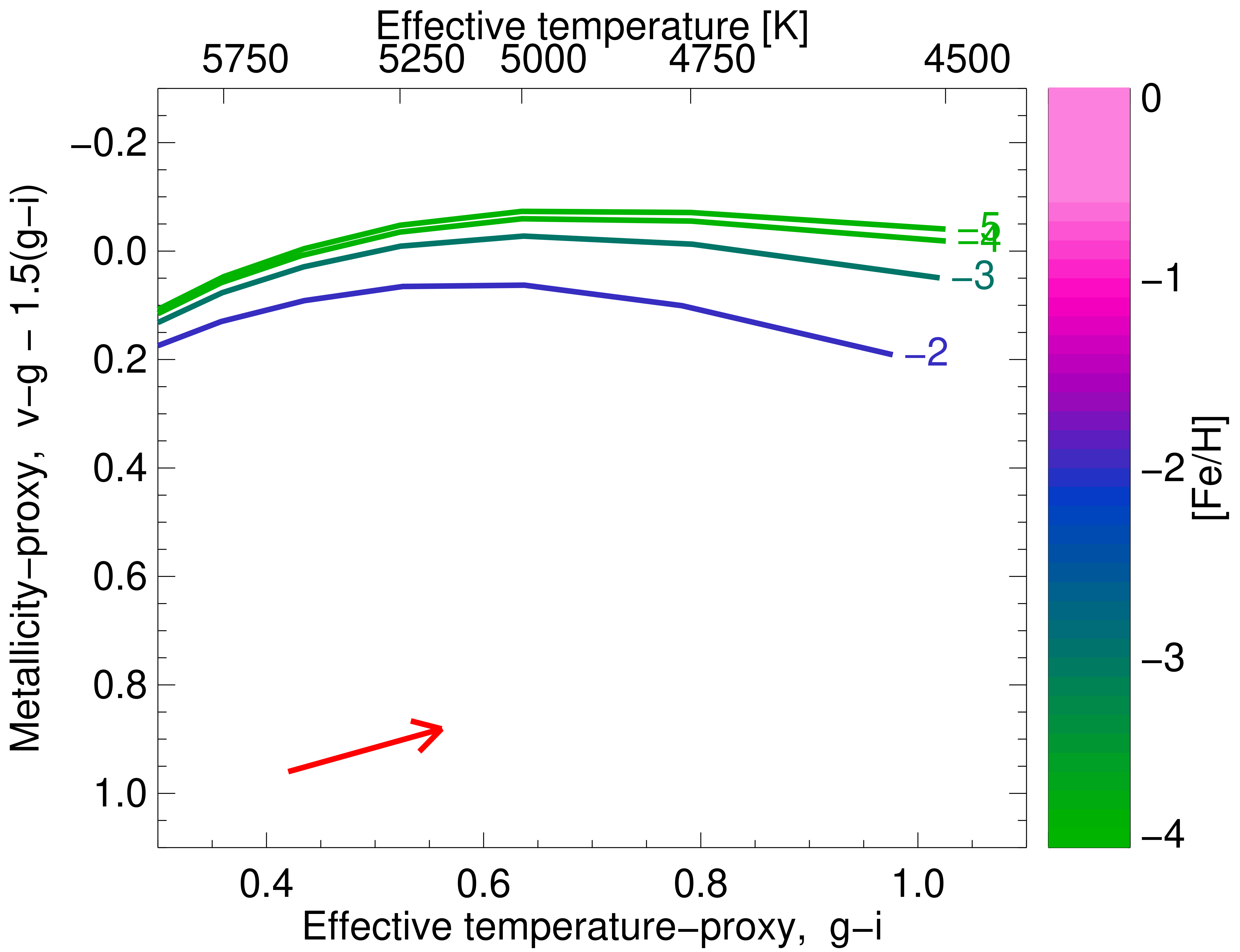

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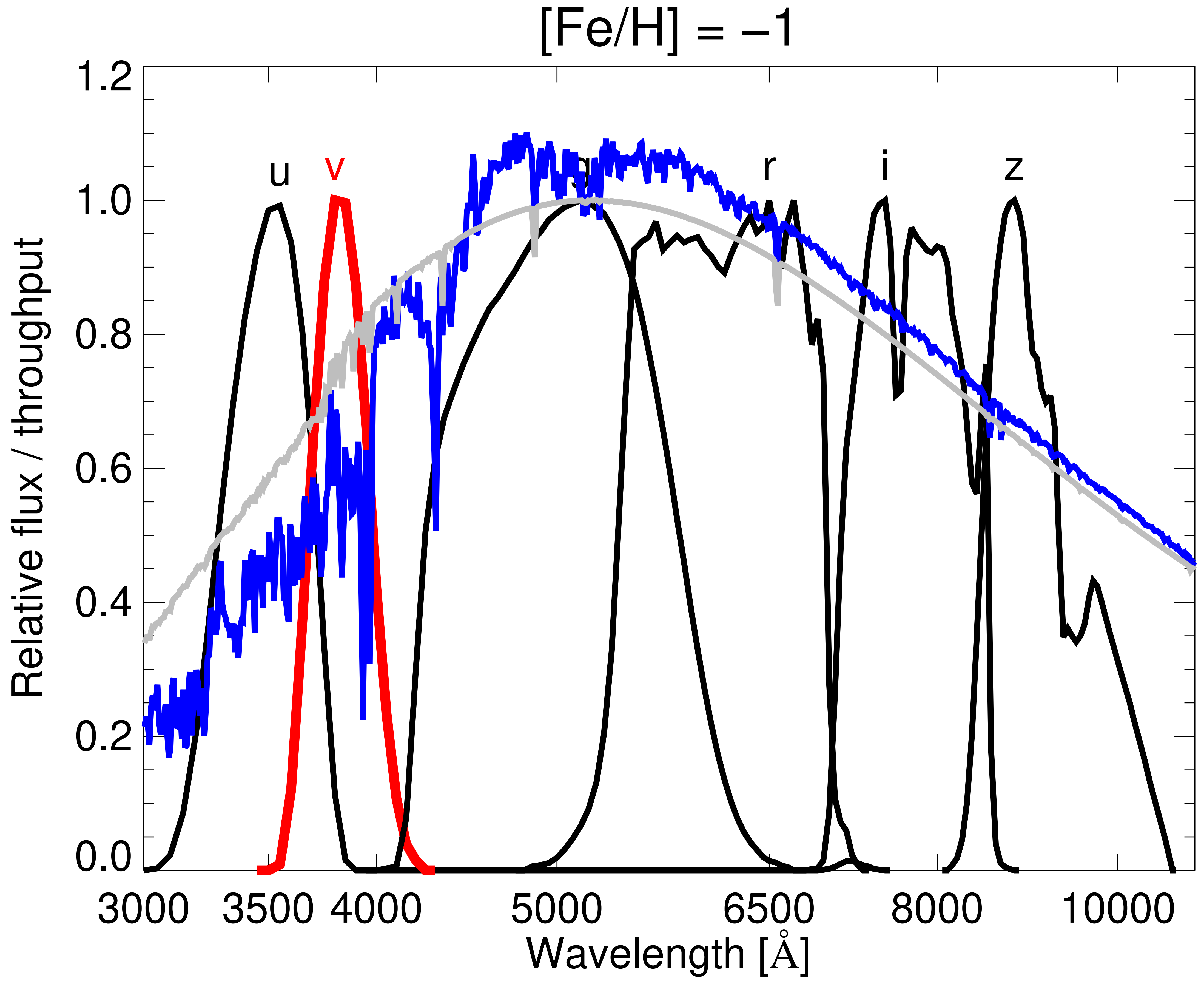

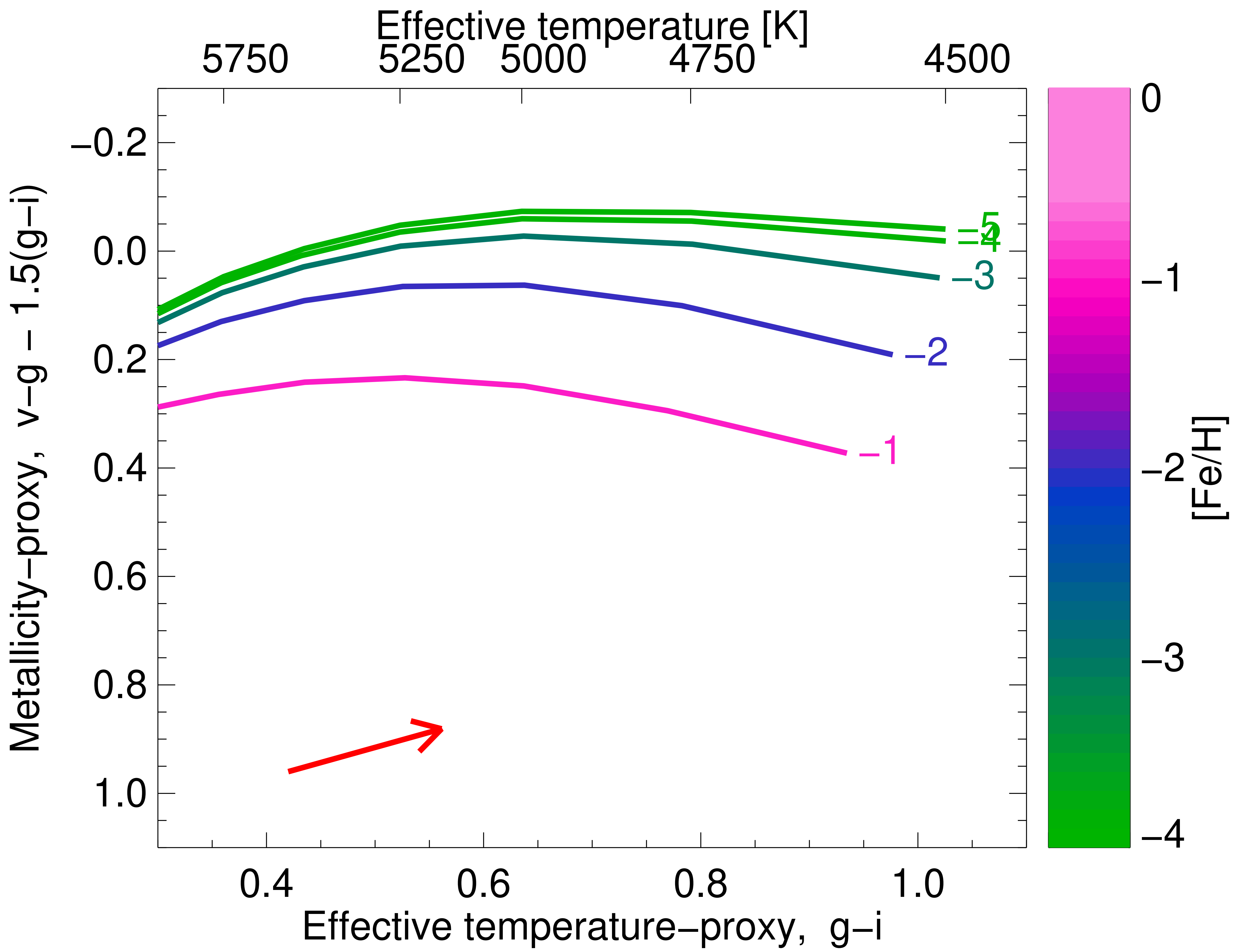

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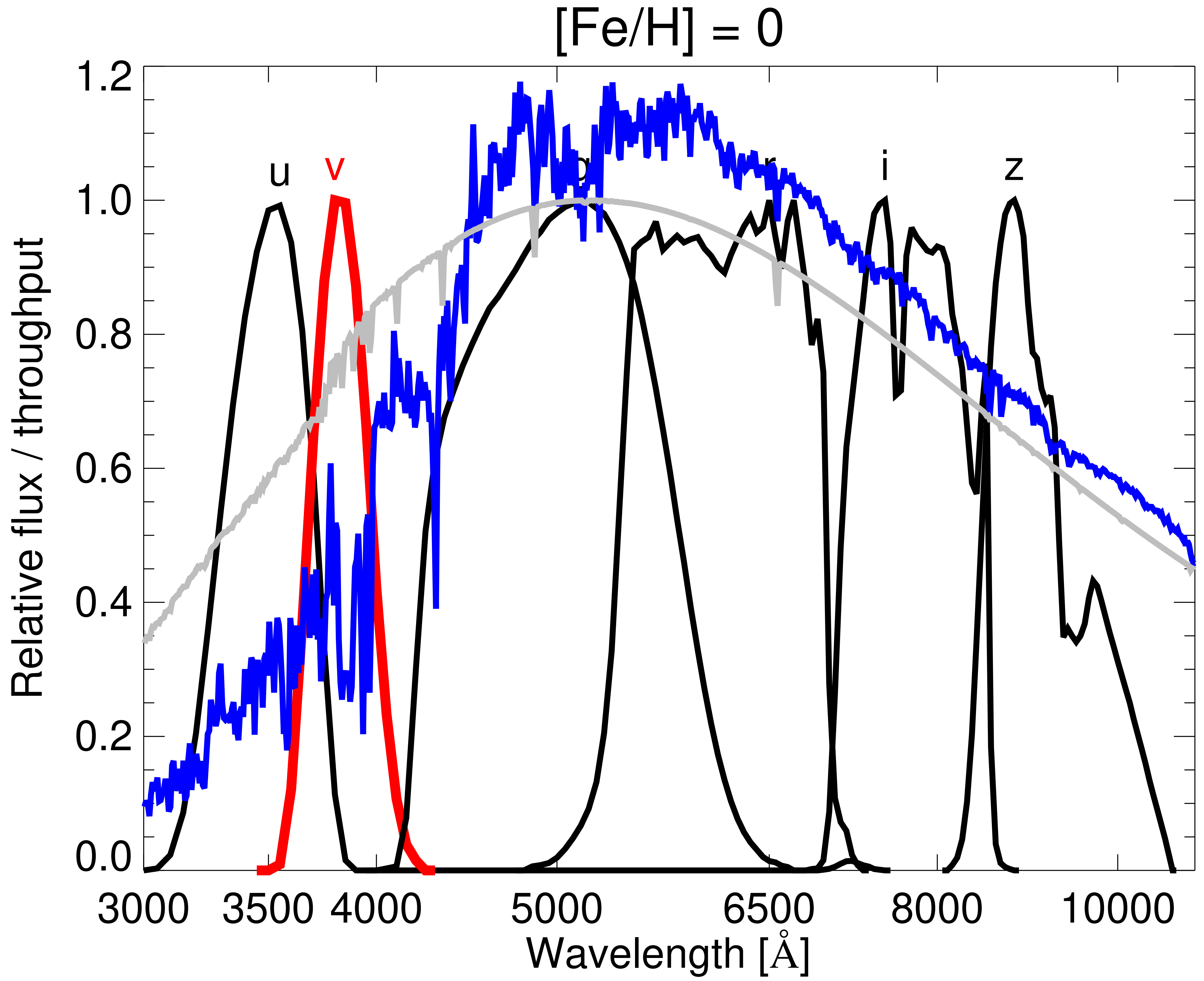

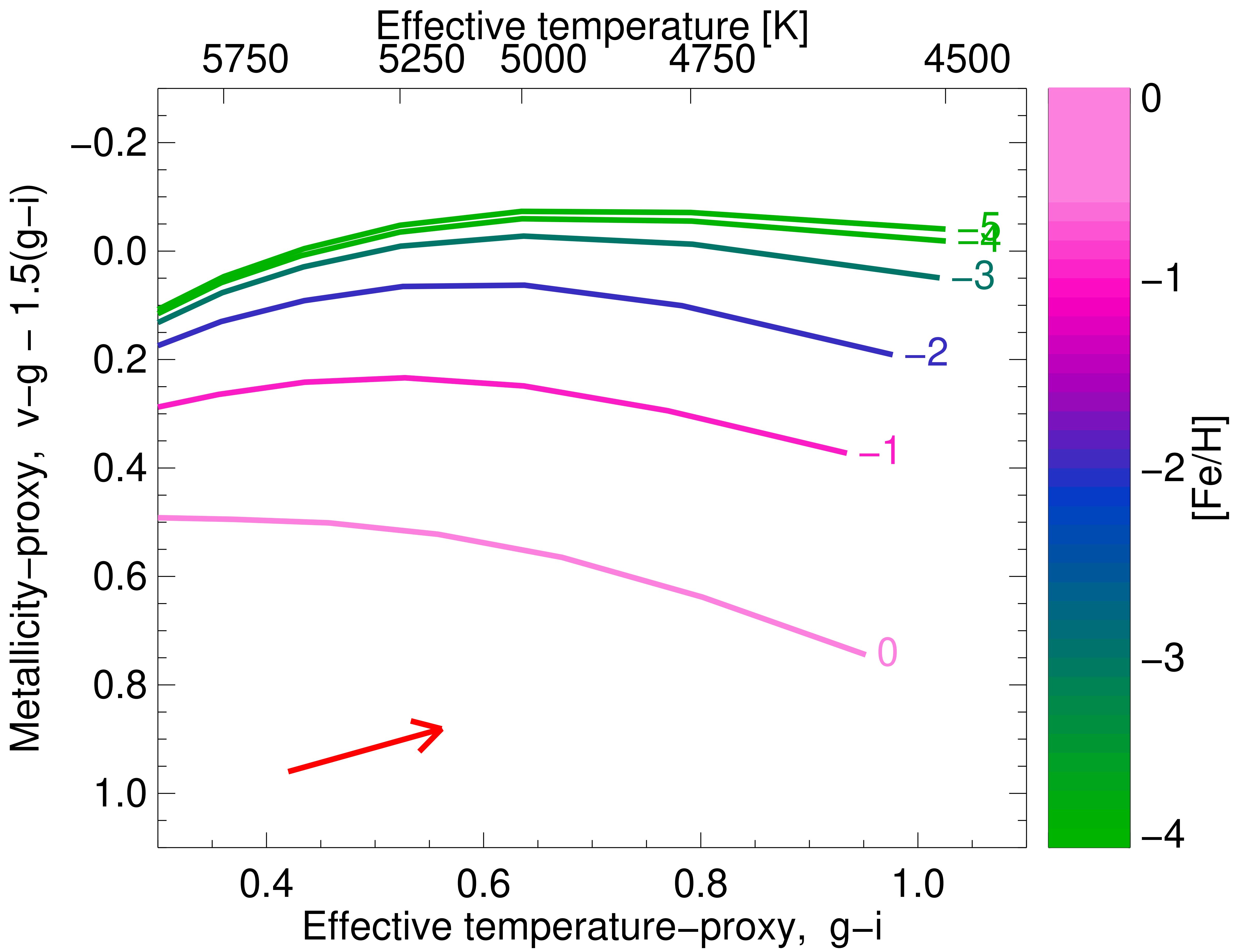

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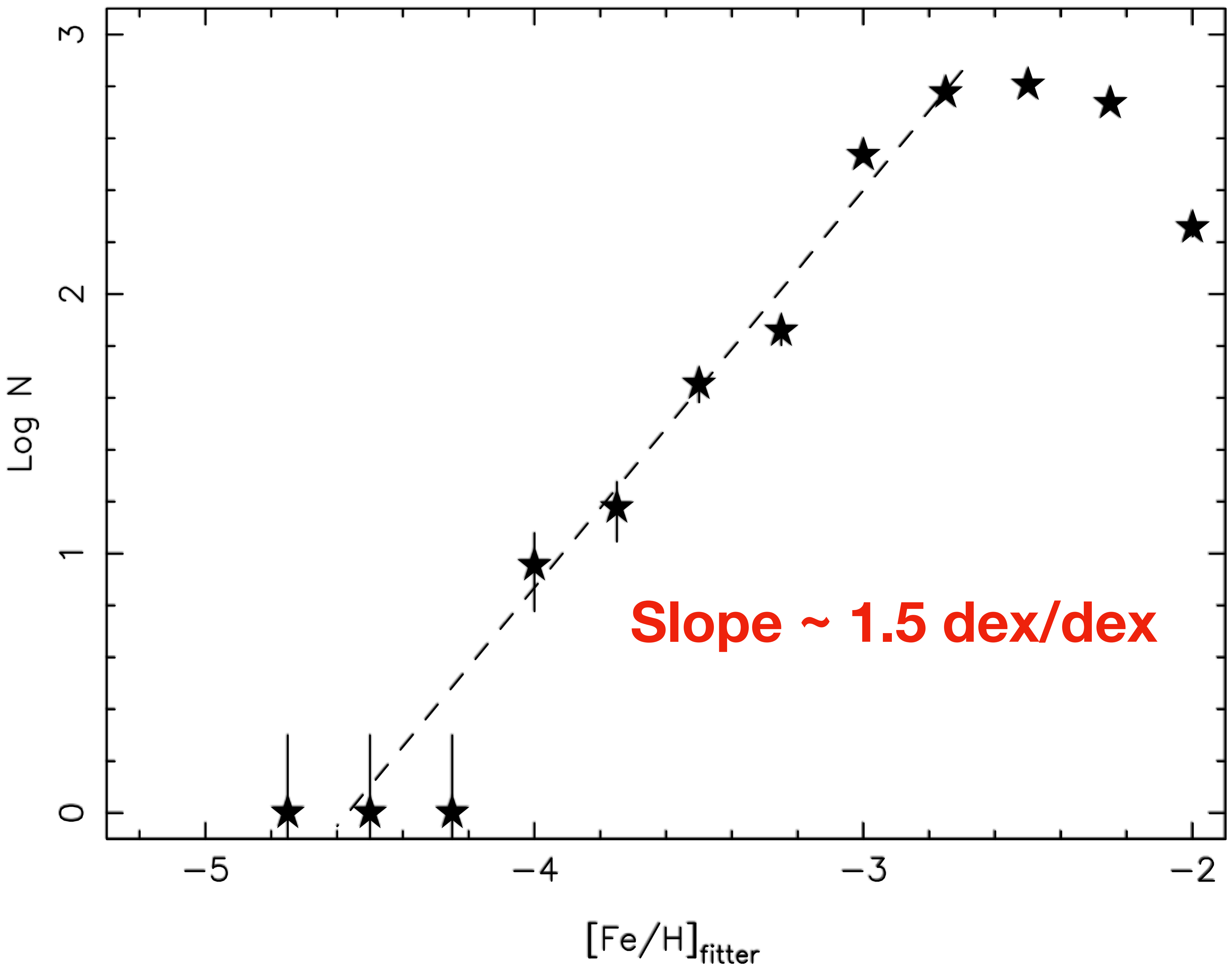
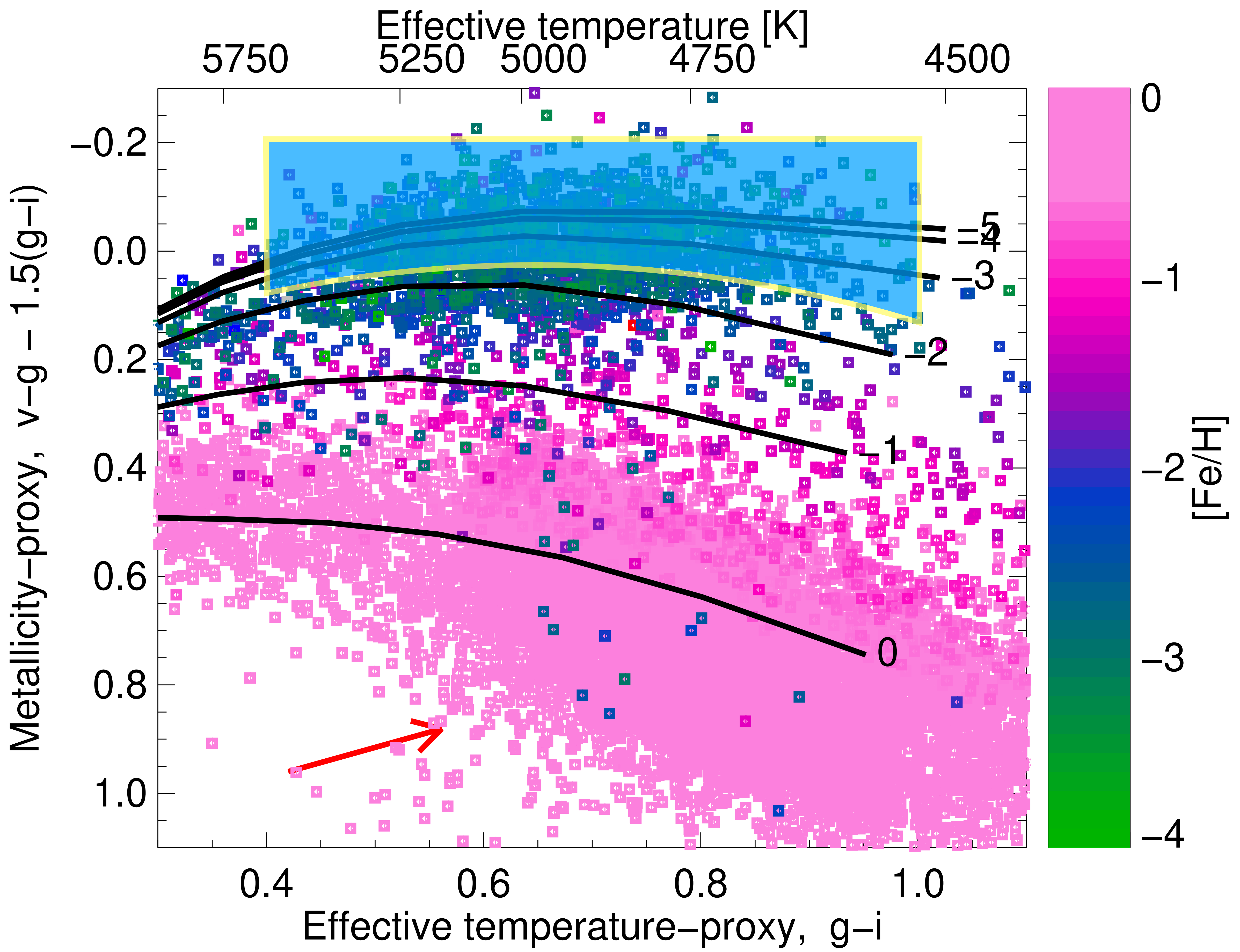
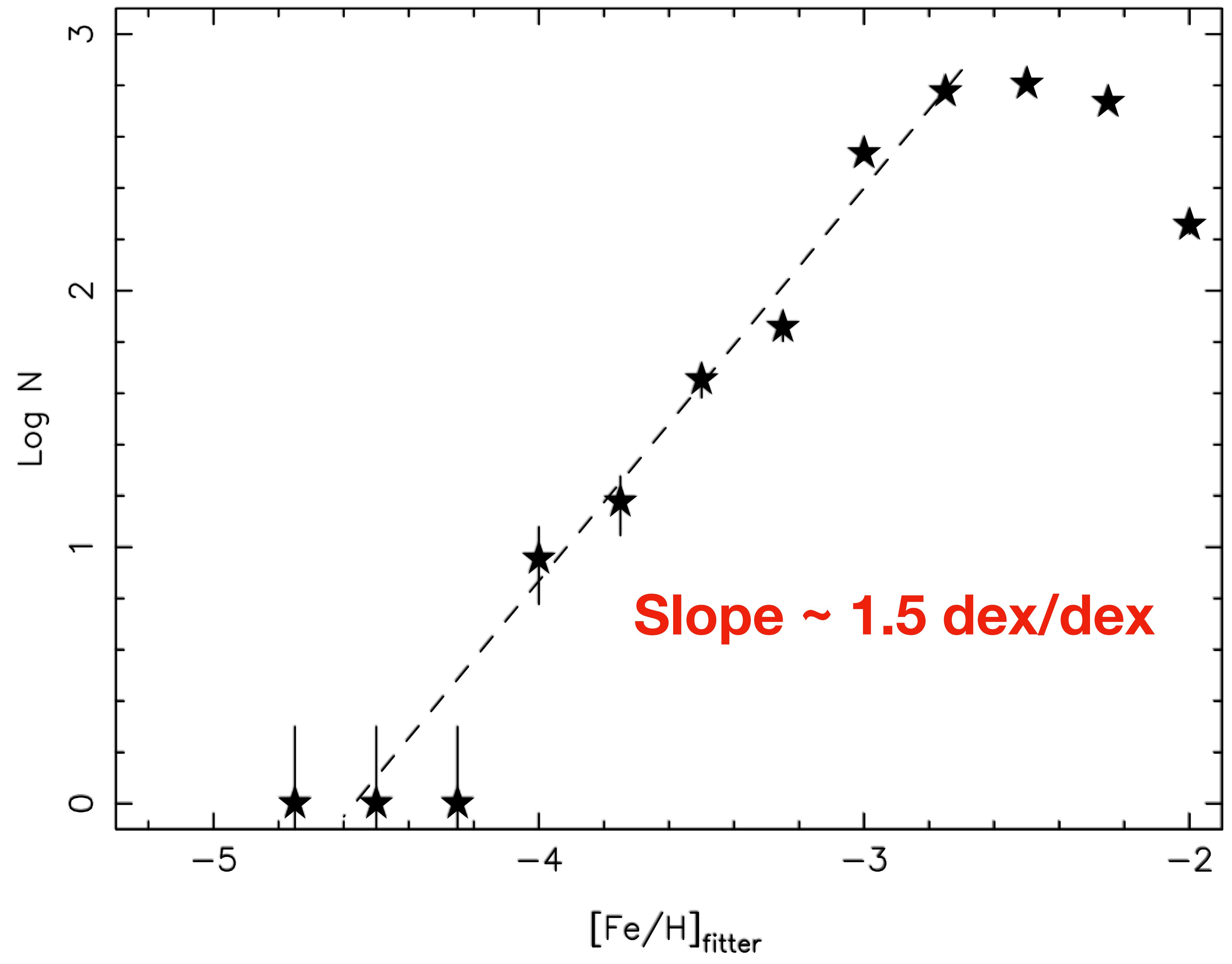


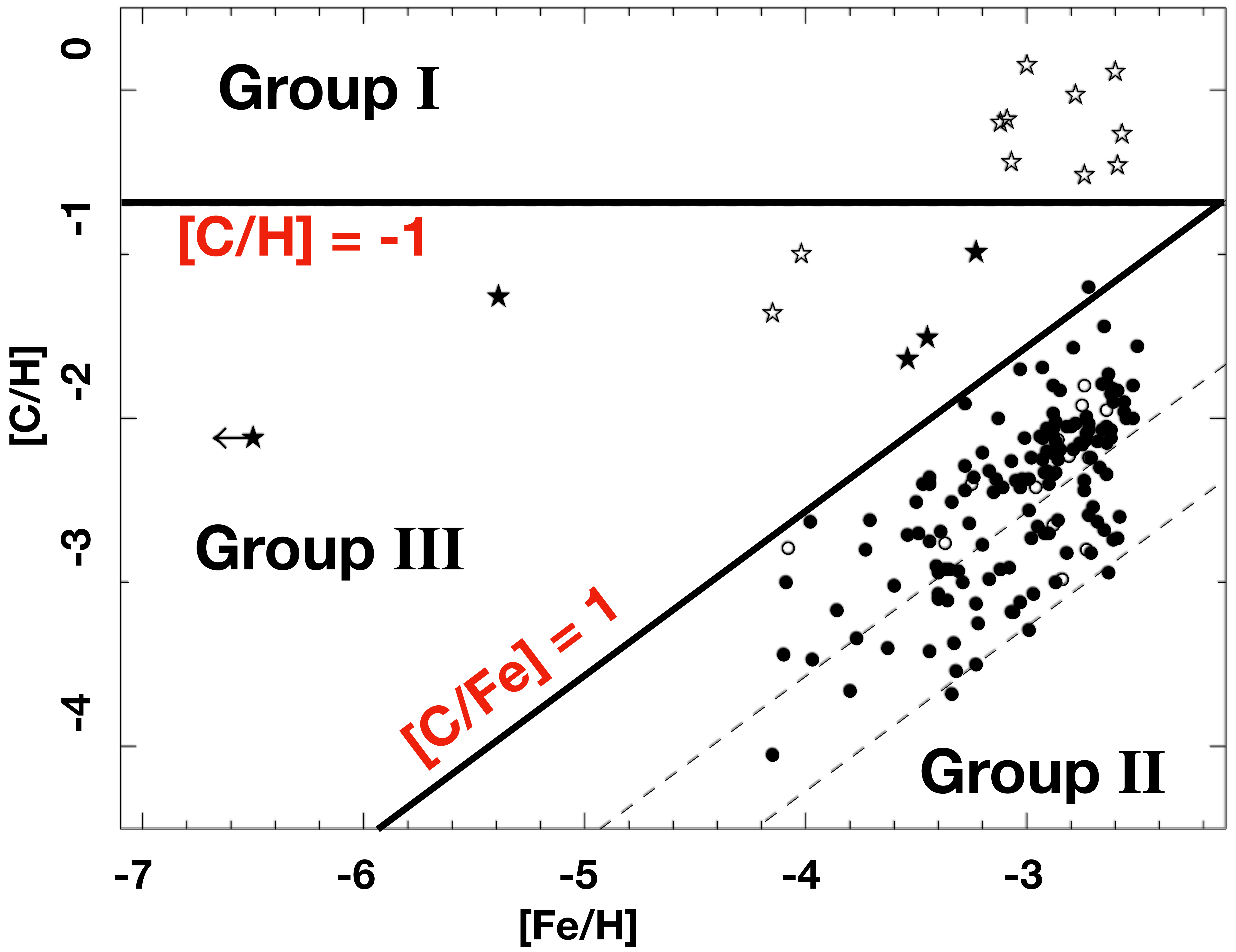


Observational data: GALAH DR2 + 2.3m + Norris (priv)

Da Costa, Bessell, Mackey, TN+ submitted

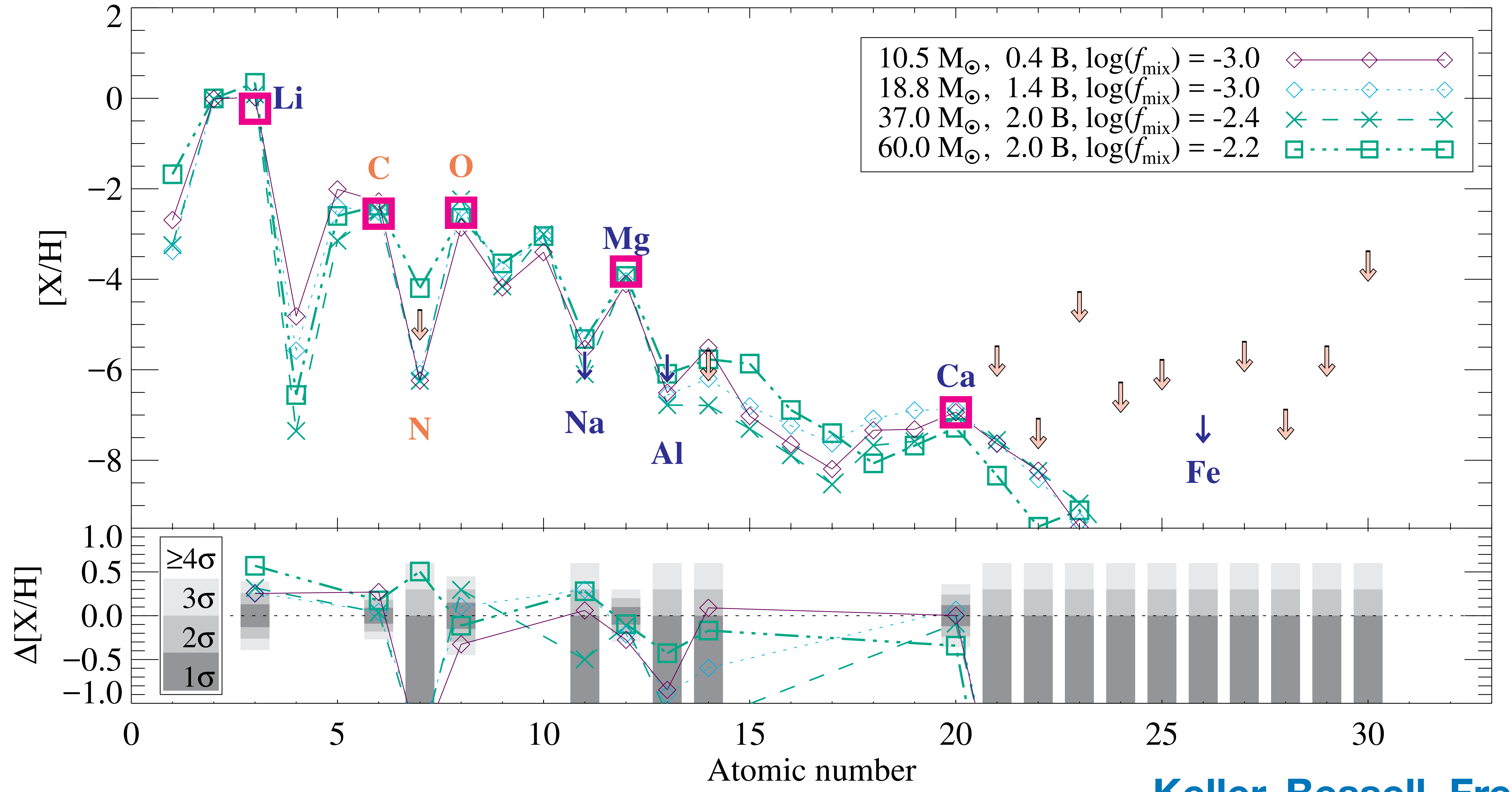
The SkyMapper EMP search





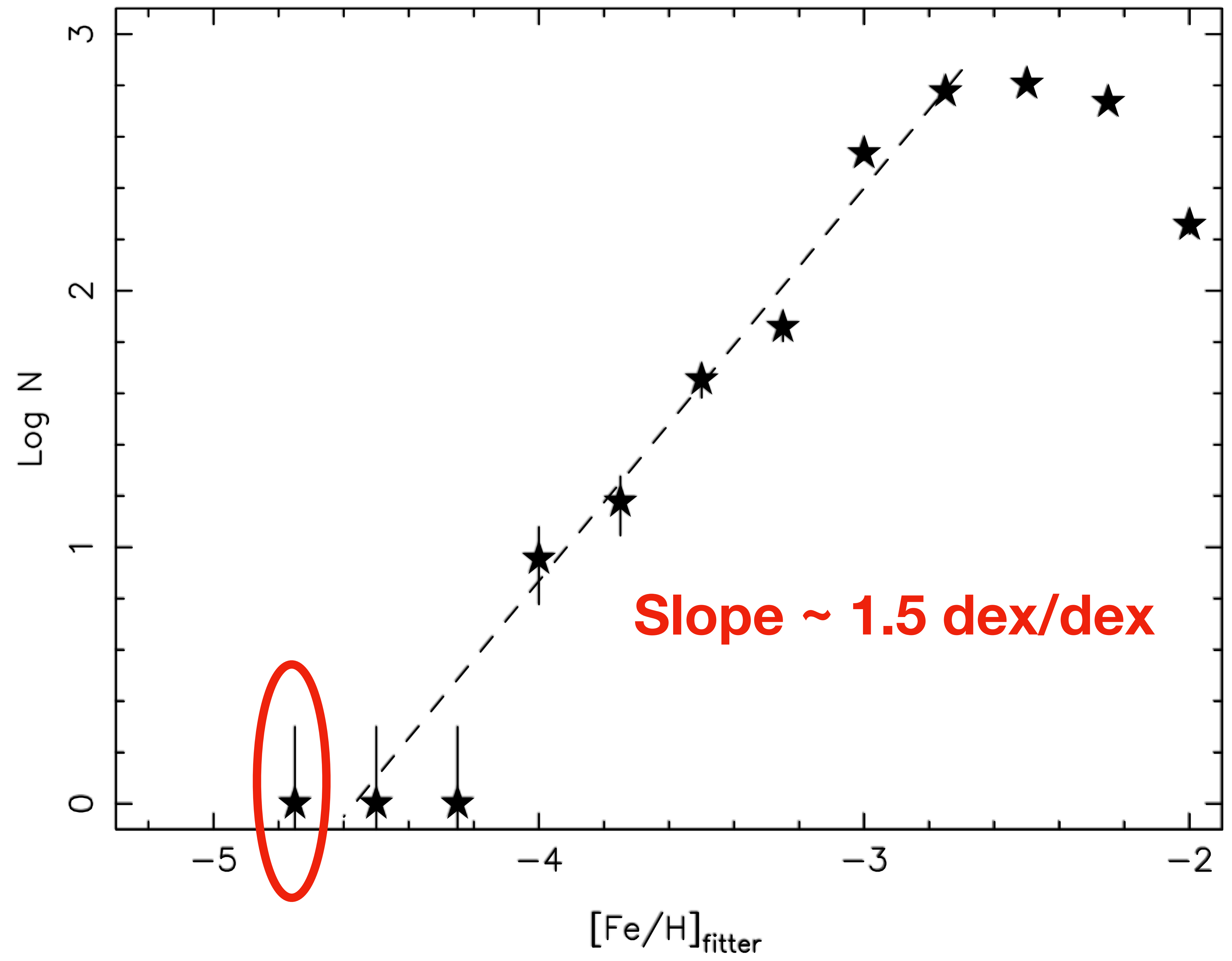
Da Costa, Bessell, Mackey, TN+ submitted

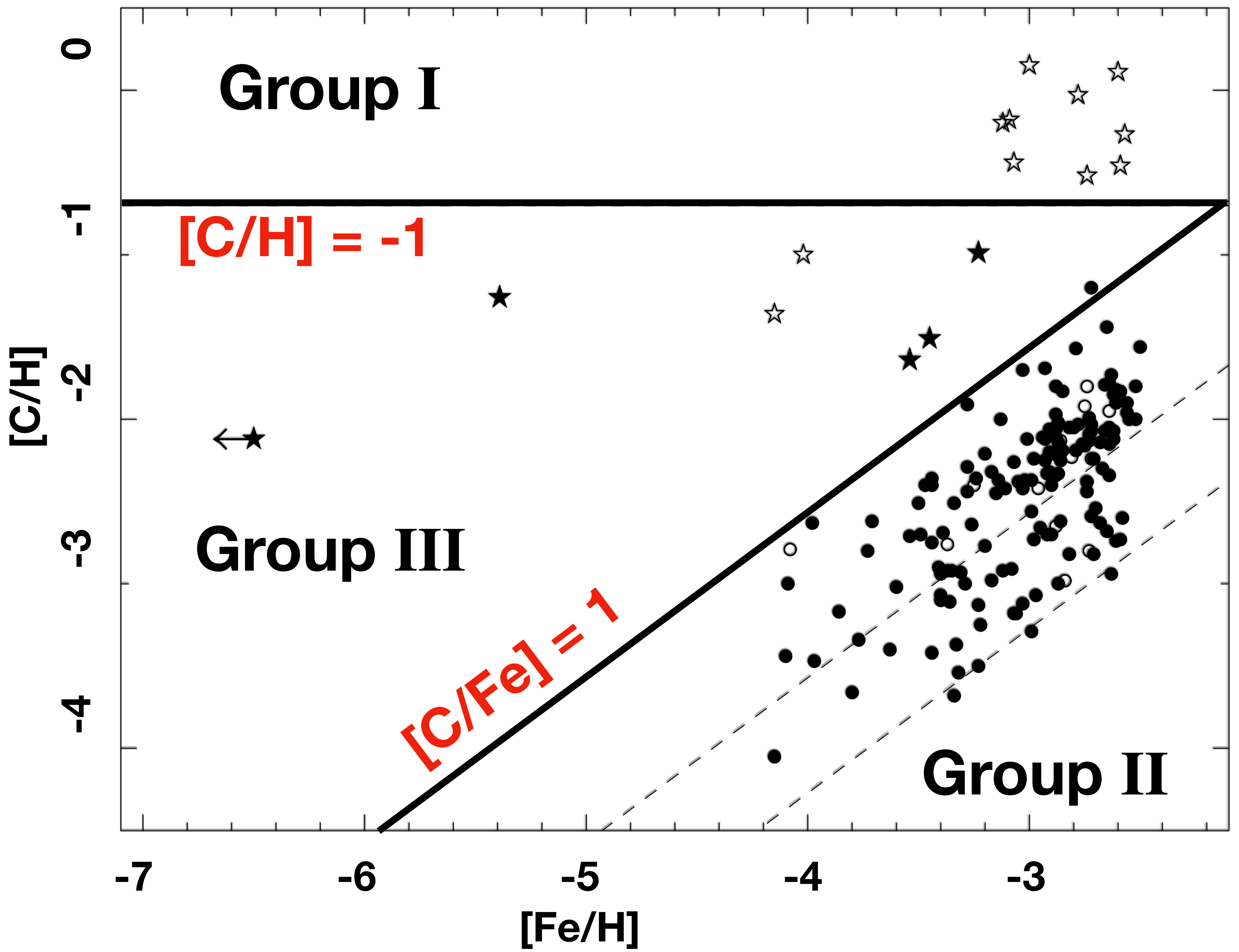
SMSS 0313-6708: [Fe/H] < -6.5



Keller, Bessell, Frebel+ 2014
TN, Amarsi, Lind+ 2017

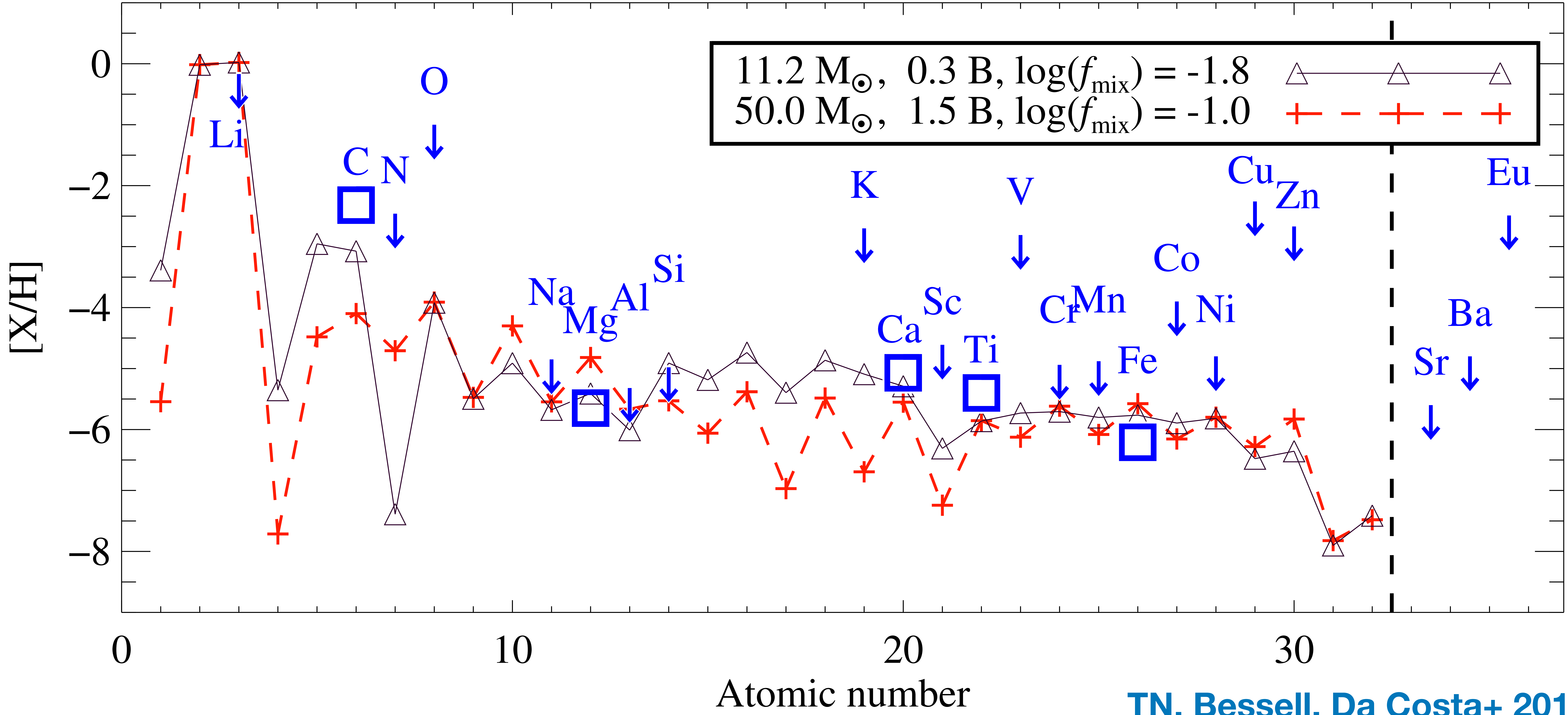
The SkyMapper EMP search





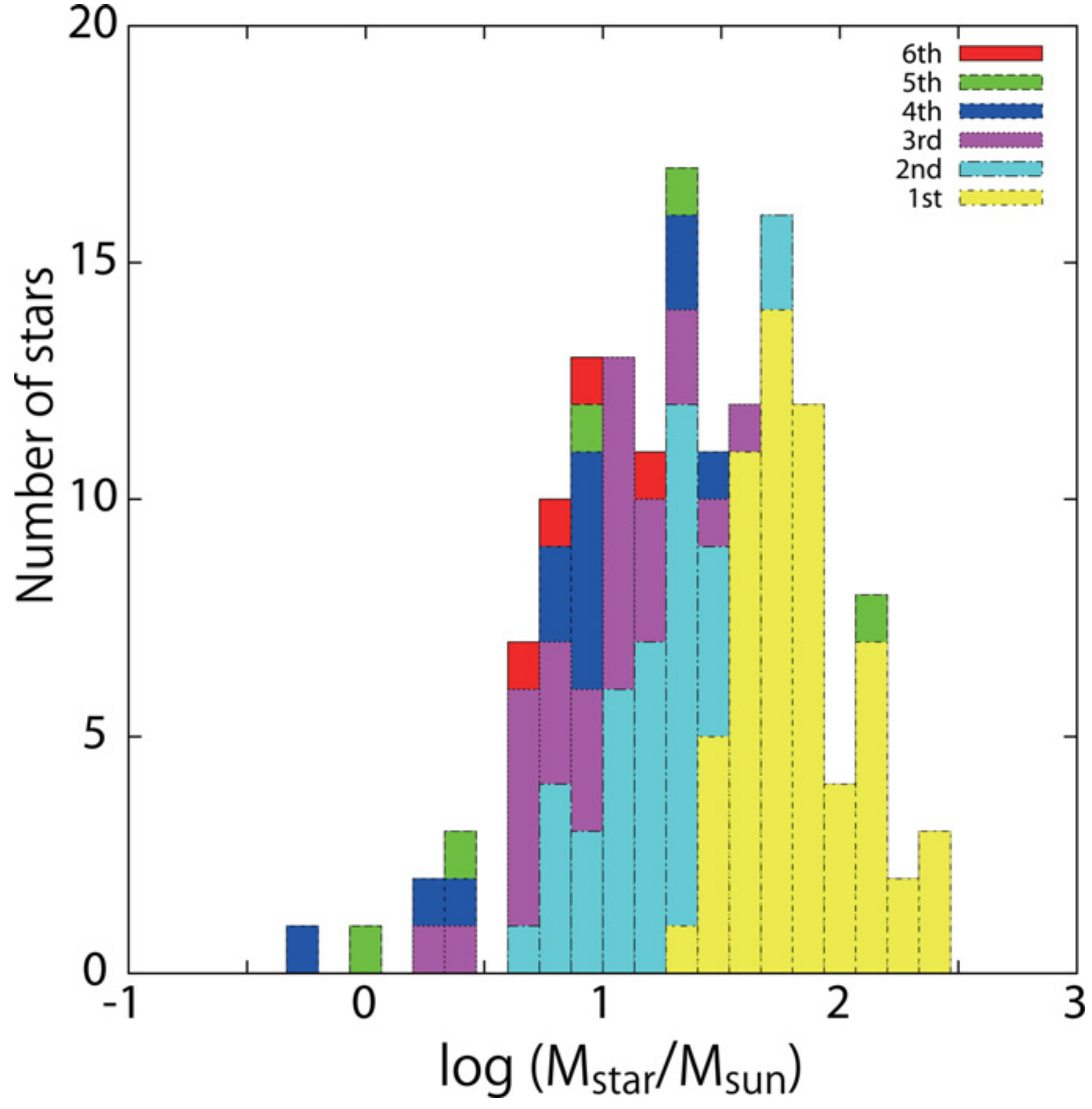
Da Costa, Bessell, Mackey, TN+ submitted

The first [Fe/H] = -6 star: SMSS1605

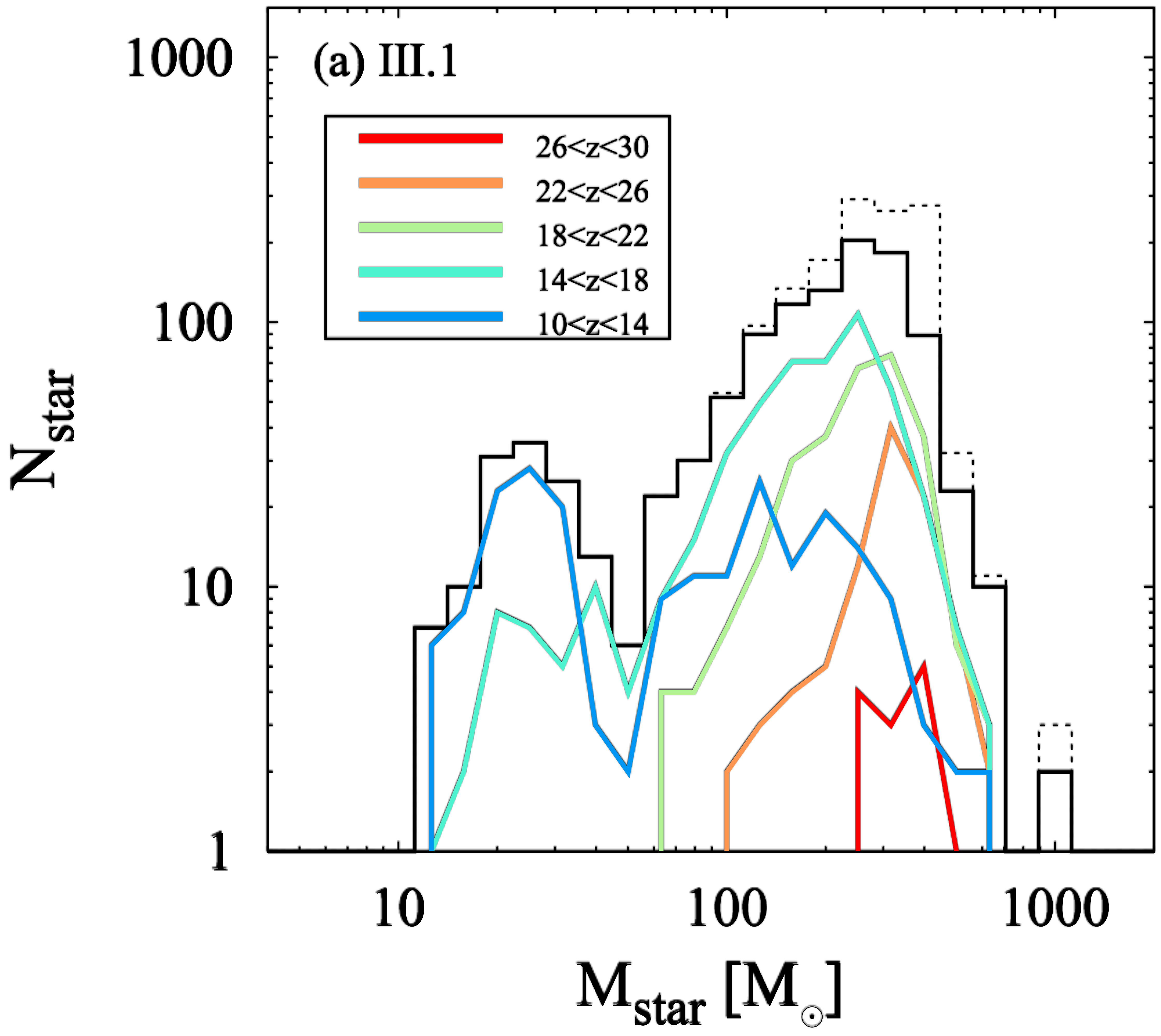


TN, Bessell, Da Costa+ 2019

Pop III IMF



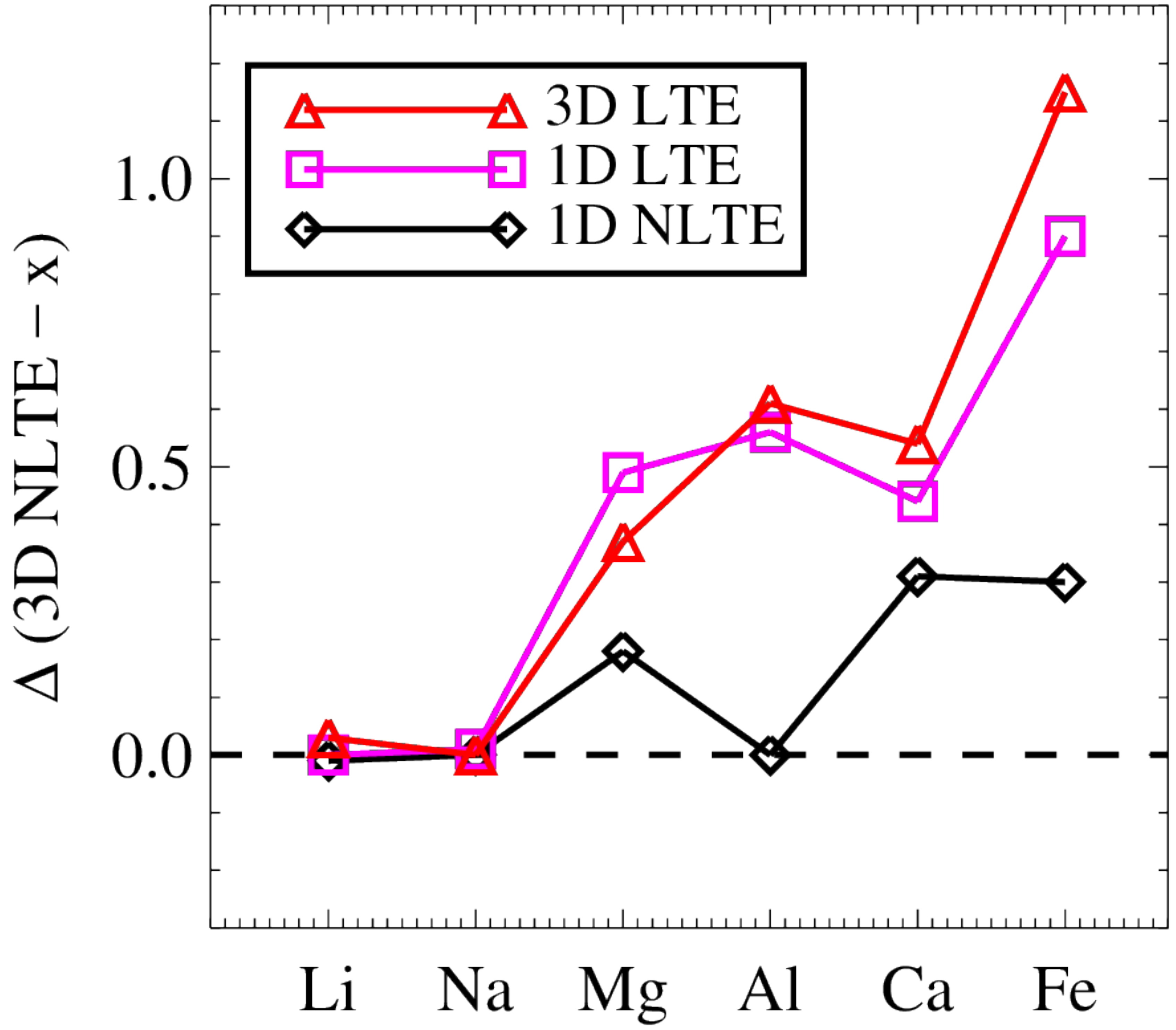
Susa, Hasegawa, Tominaga 2014

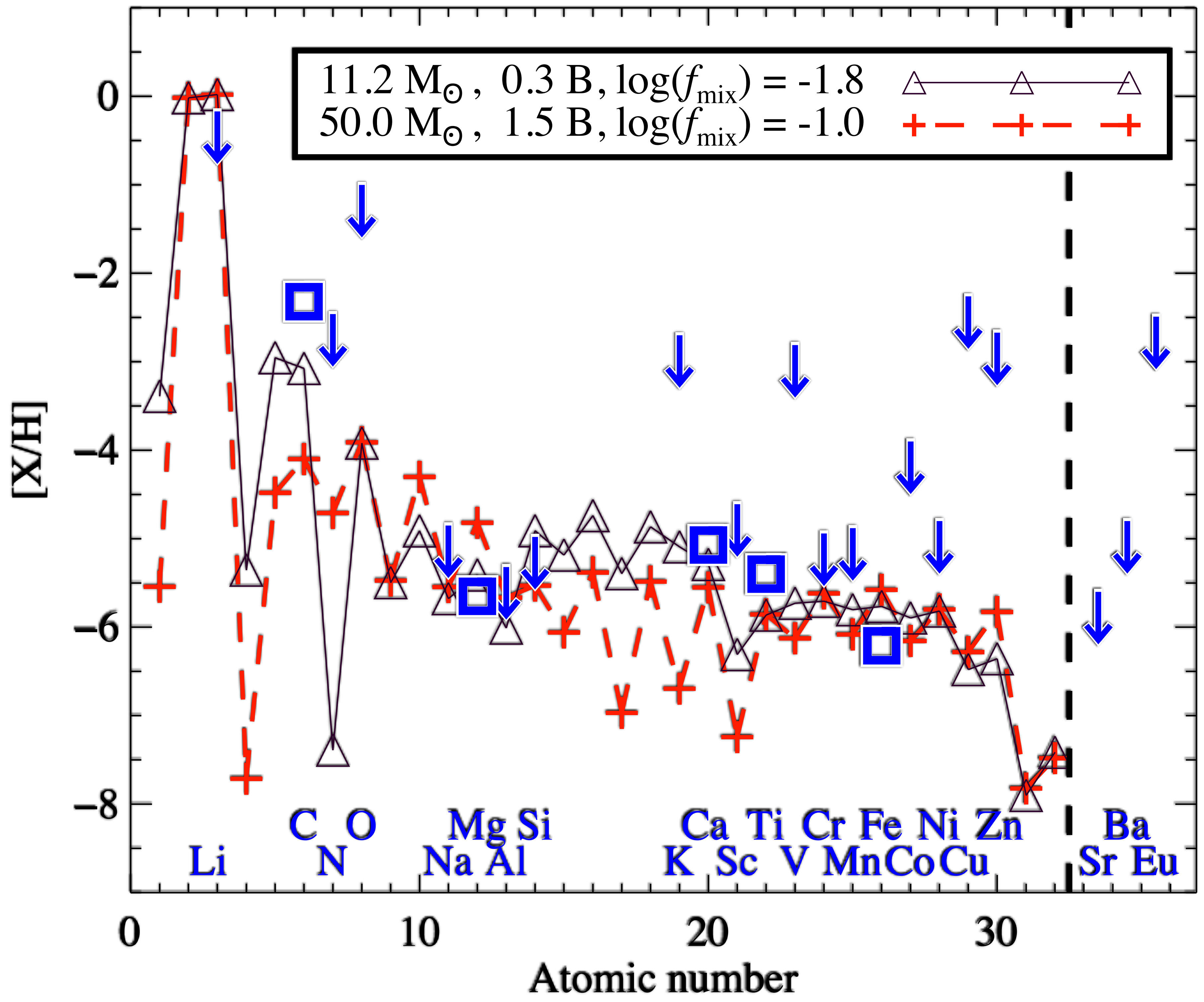


Hirano, Hosokawa, Yoshida+ 2015

Summary

- MLT good enough for stellar atmospheres?
- 3D NLTE now feasible. Use at low [Fe/H]!





- EMP MDF slope = 1.5 dex/dex
- Carbon-normal MDF drops at [Fe/H] ~ -4
- Evidence for 10 Msol Pop III star?