WP122300 pipeline

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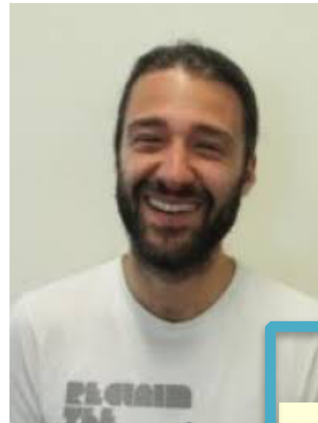
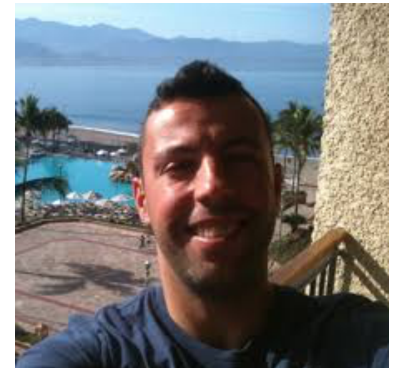
Goal of WP122300

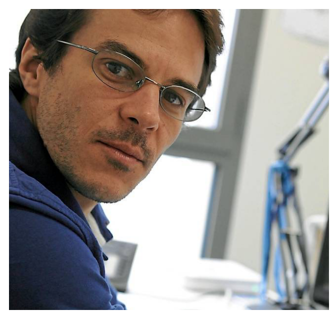
- ✓ Identify optimal algorithms to fold-in different observational datasets for a star
  e.g. spectra, photometry, asteroseismology, interferometry, parallax, etc
- ✓ Develop a pipeline for the determination of <u>classical</u> parameters for PLATO targets
  Teff, log(g), [Fe/H], chemical abundances, radius, luminosity
- ✓ Provide working source code for the pipeline

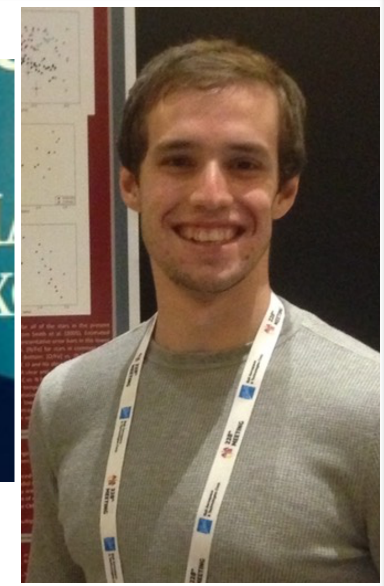
WP122 Development and Management Plan, issue 3

WP122300



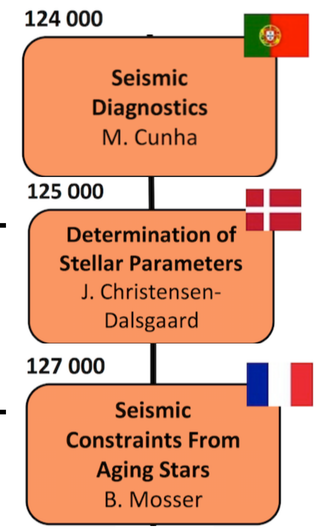





More than 20 scientists with expertise in model atmospheres (both 1D and 3D), spectral modelling, (spectro)photometry, interferometry, SED fitting, Bayesian methods and astro-statistics, and analysis of fundamental stellar parameters.

Requirements on WP122300 deliverables

Primary parameter	Error*	Users
✓ Stellar radius	2%	exoplanet WPs
✓ Luminosity	5%	WPs: 124, 125, 127
✓ T_{eff}	1%	WPs: 124, 125, 127 + exoplanet WPs
✓ [Fe/H], chemical abundances	< 0.1 dex	WPs: 124, 125, 127 + exoplanet WPs



Stellar Science Definition of Specifications: WP122

PLATO-ULG-PSPM-DRD-006, issue 1, rev 0

* preliminary

Impact of stellar parameters on the determination of masses and ages

	Goal	Impact error in classical parameter	
		ΔTeff = 100 K	Δ[Fe/H] = 0.1 dex
$\Delta R/R$	2%	~1%	~1%
$\Delta M/M$	10%	~3%	~3%
$\Delta\tau/\tau$	10%	~10%	~4%

Based on studies from Serenelli+17, Valle+18, and Bellinger+19

Pipeline requirements

- ✓ Observed targets: FGKM main-sequence stars and subgiants (PLATO P1, P2, P4, P5 catalogues)

- ✓ Robust and efficient analysis (T_{eff}, [Fe/H] …) of $3x10^5$ stars
  fully-automated numerically stable module, minimal human intervention

- ✓ Combination of diverse (& heterogeneous) data sequences, outputs in the form of Probability Distribution Functions
  spectra, photometry, parallax, asteroseismology, interferometry

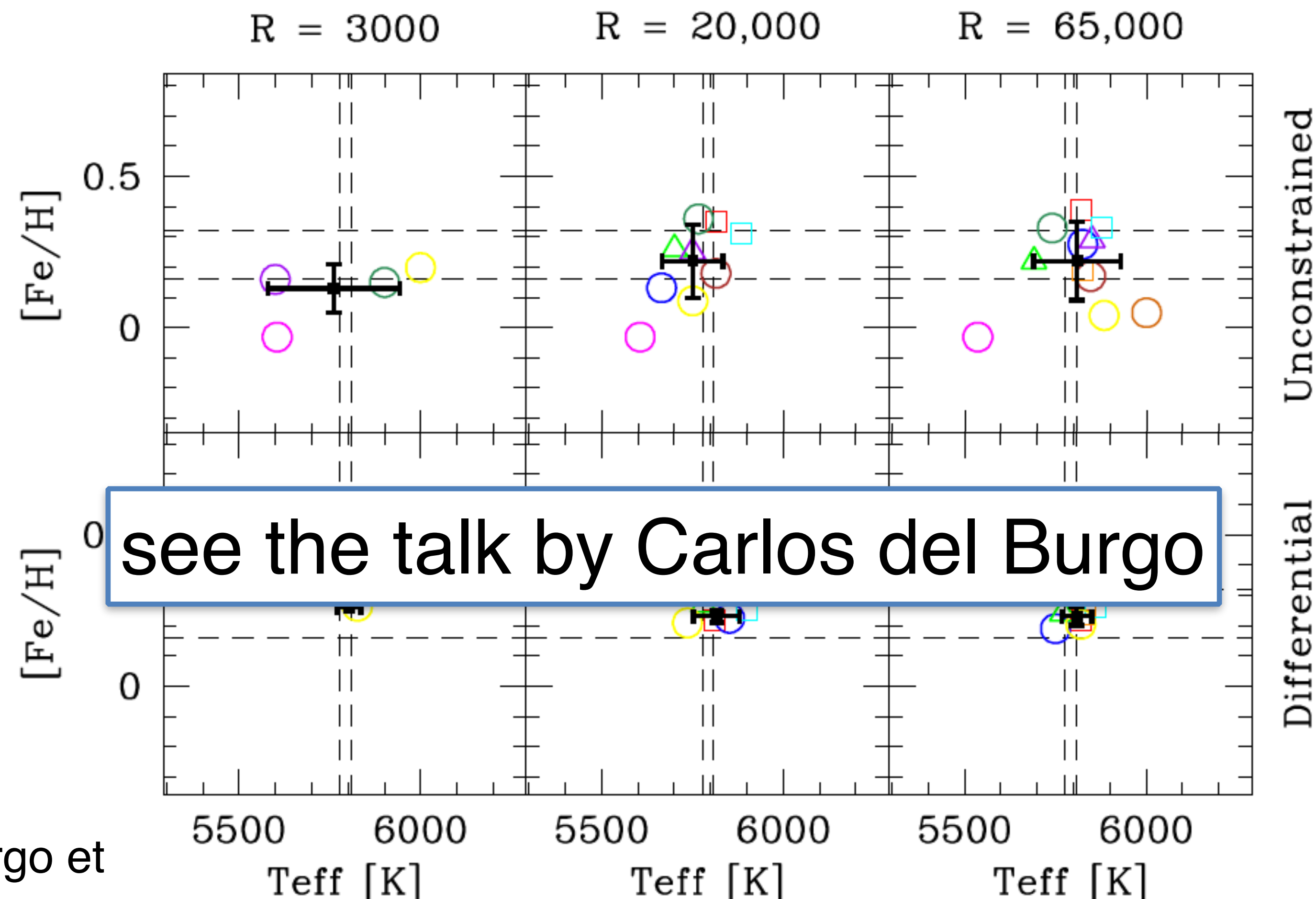
- ✓ Flexibility and ability to accommodate state-of-the-art physics
  synthetic spectra, stellar evolution models

- ✓ Verification, reproducibility
  open-source project (GitHub), extensive documentation, continuous updates, multi-stage quality assurance process, quick re-processing

Where do we stand?

WP122300: progress so far

- ✓ tested different methods for spectroscopic analysis
  H&H campaign (PLATO-ULG-PSPM-TN-0036)



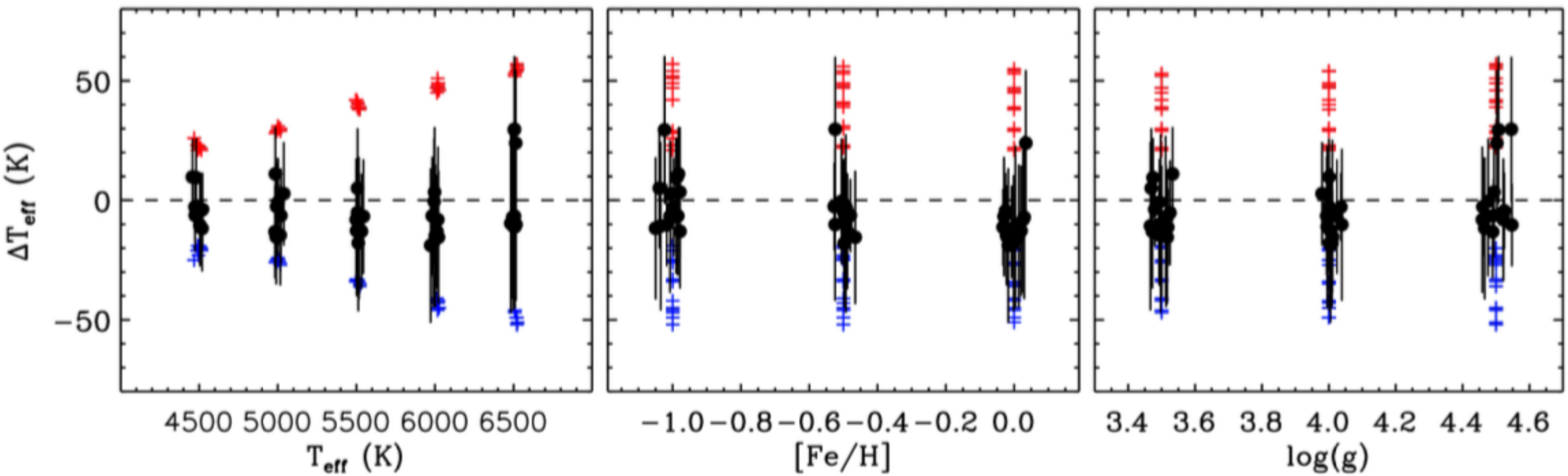
see the talk by Carlos del Burgo

del Burgo et al. in prep.

WP122300: progress so far

- ✓ tested different methods for spectroscopic analysis
  H&H campaign (PLATO-ULG-PSPM-TN-0036)

- ✓ tested and reported on the IRFM method (PLATO-ANU-PSPM-TN-0055)
  T_{eff} at ~ 1%



Casagrande and Gonzalez Hernandez

WP122300: progress so far

- ✓ tested different methods for spectroscopic analysis H&H campaign (PLATO-ULG-PSPM-TN-0036)
- ✓ tested and reported on the IRFM method (PLATO-ANU-PSPM-TN-0055) T_{eff} at ~ 1%
- ✓ tests of interferometry, SED fitting, and SBCR in progress (TN in prep.)

WP122300: progress so far

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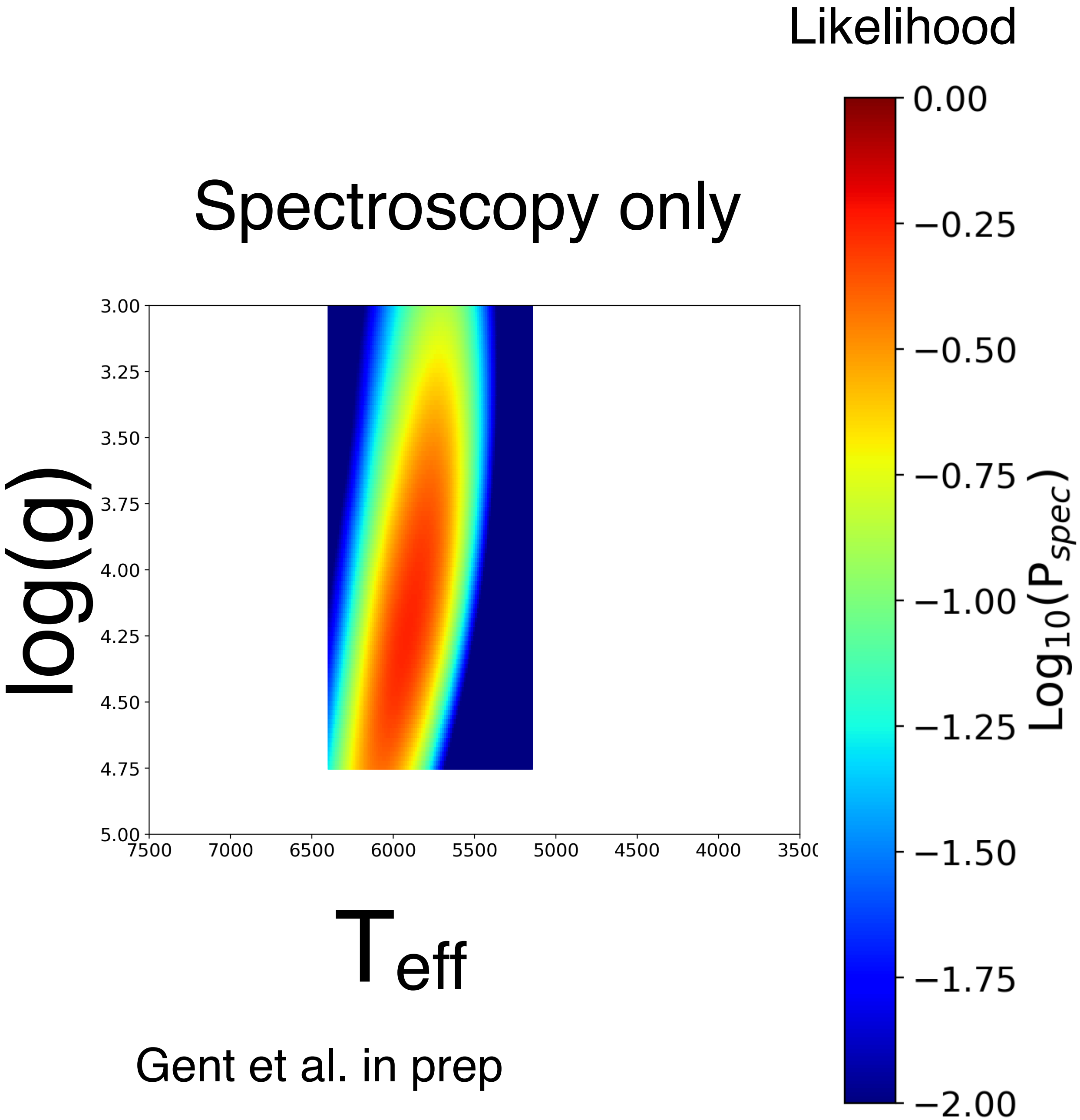
  T_{eff} at ~ 1%
- ✓ tests of interferometry, SED fitting, and SBCR in progress
  (TN in prep.)
- ✓ developed the PLATO pipeline prototype = Bayesian

Why Bayesian?

Why Bayesian?

- **photometry**: reddening, limited validity of calibrations
- **spectra**: lots of diagnostic features in a typical stellar spectrum, but each line suffers from its own systematics (imperfect physical models…)
- **distance**: not a 1-to-1 relation with parallax
- usually manual intervention, heavy line selection need, re-weighing, ad-hoc “corrections” or just loss of data…

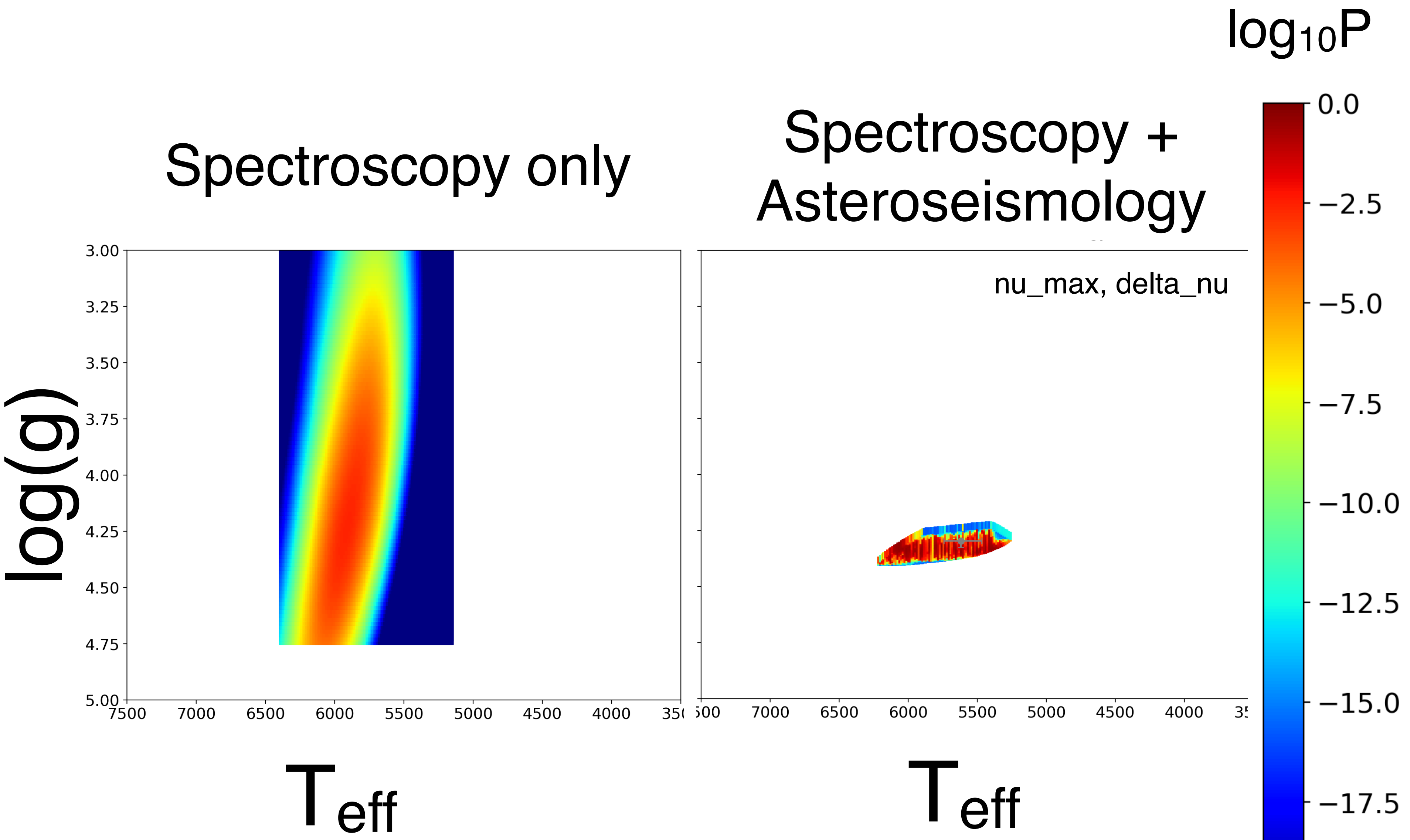
Spectroscopy only



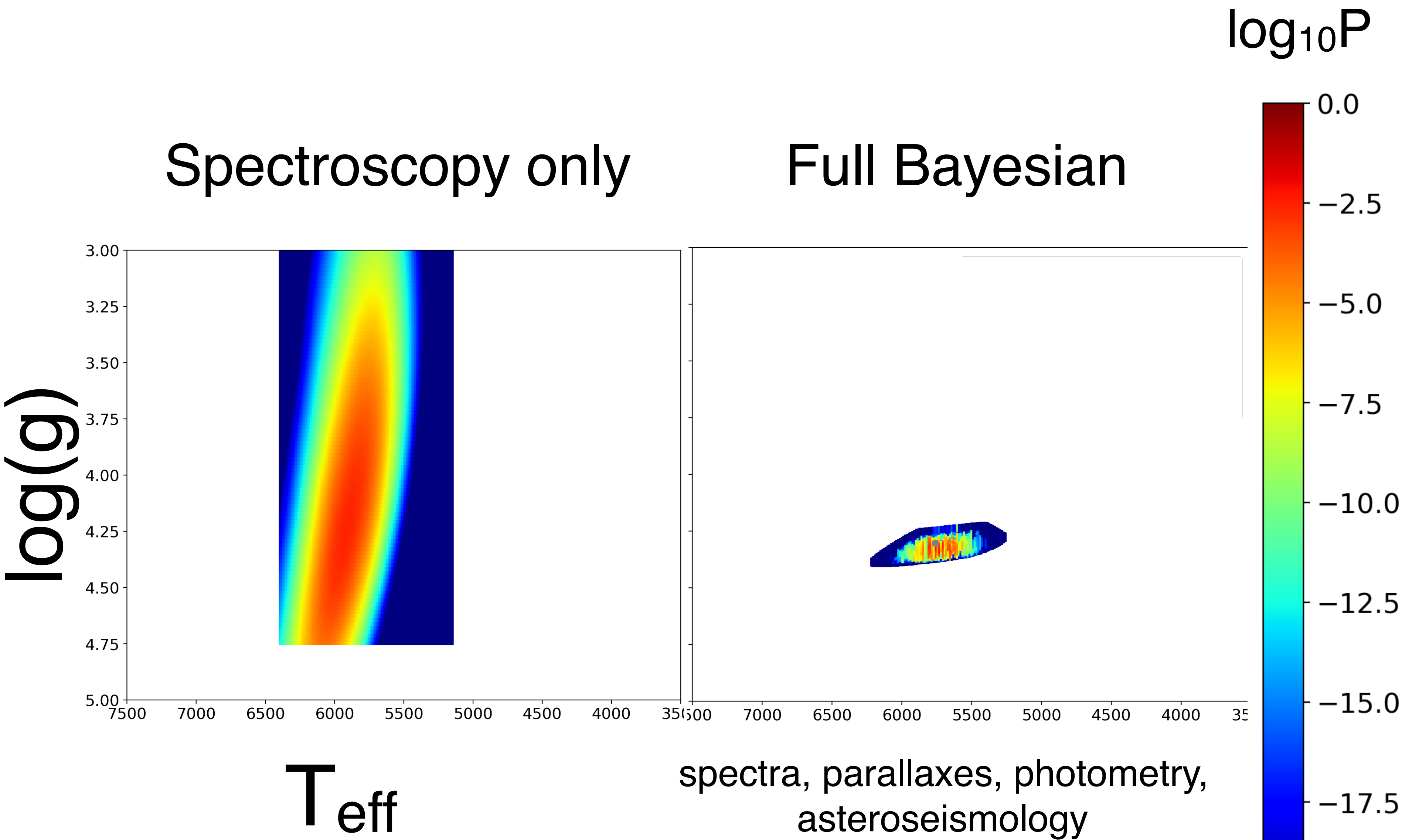
Gent et al. in prep

Spectroscopy only

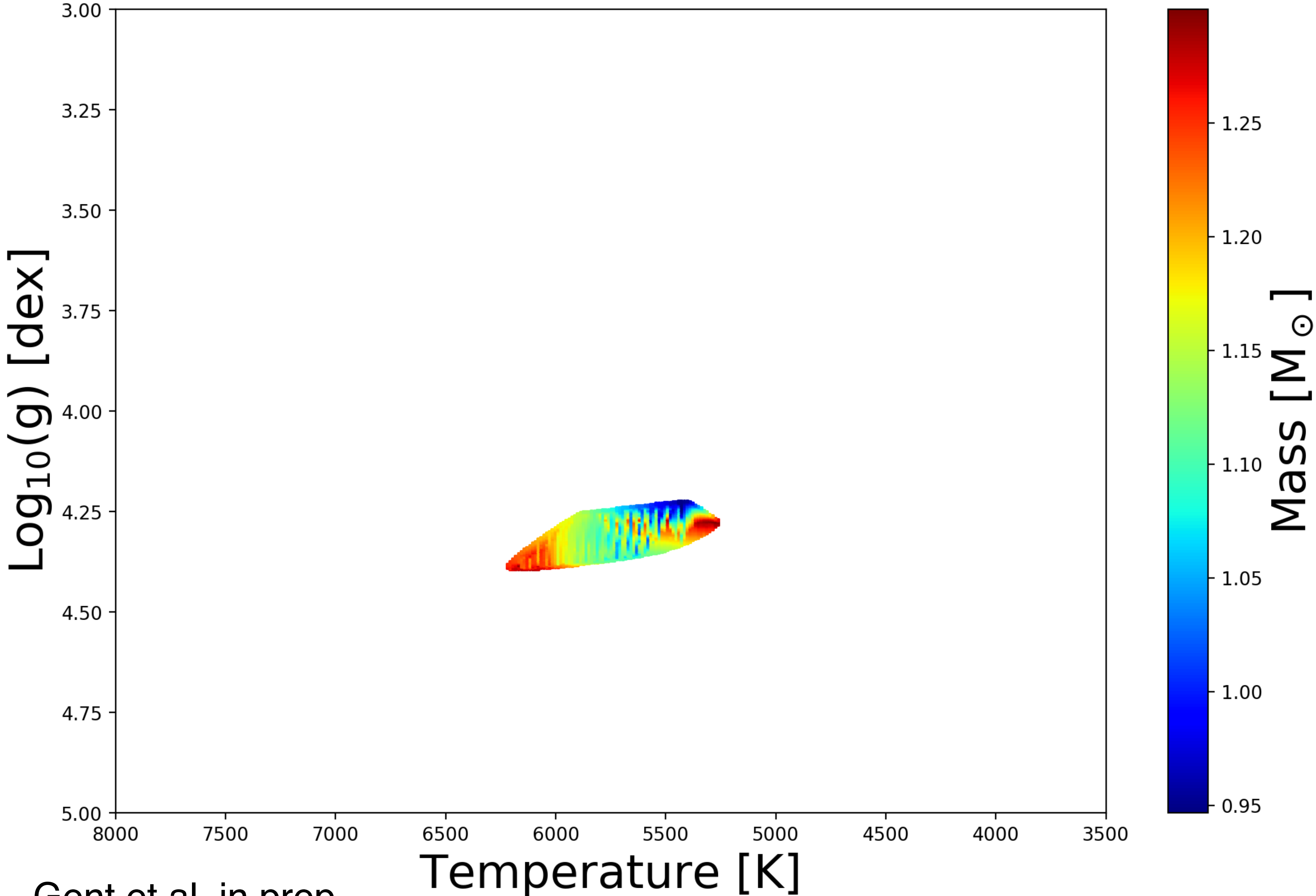
Spectroscopy + Asteroseismology



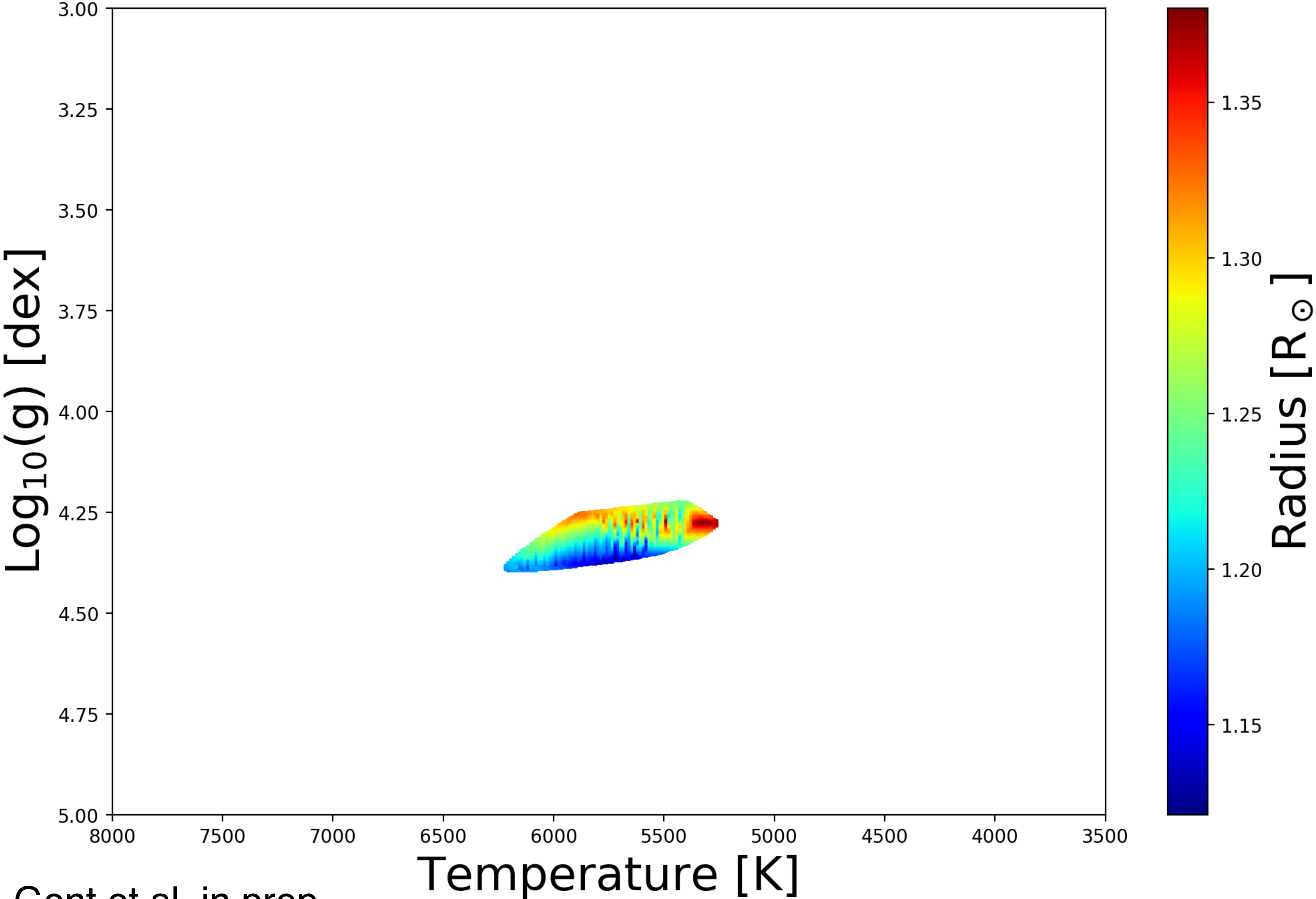
Gent et al. in prep



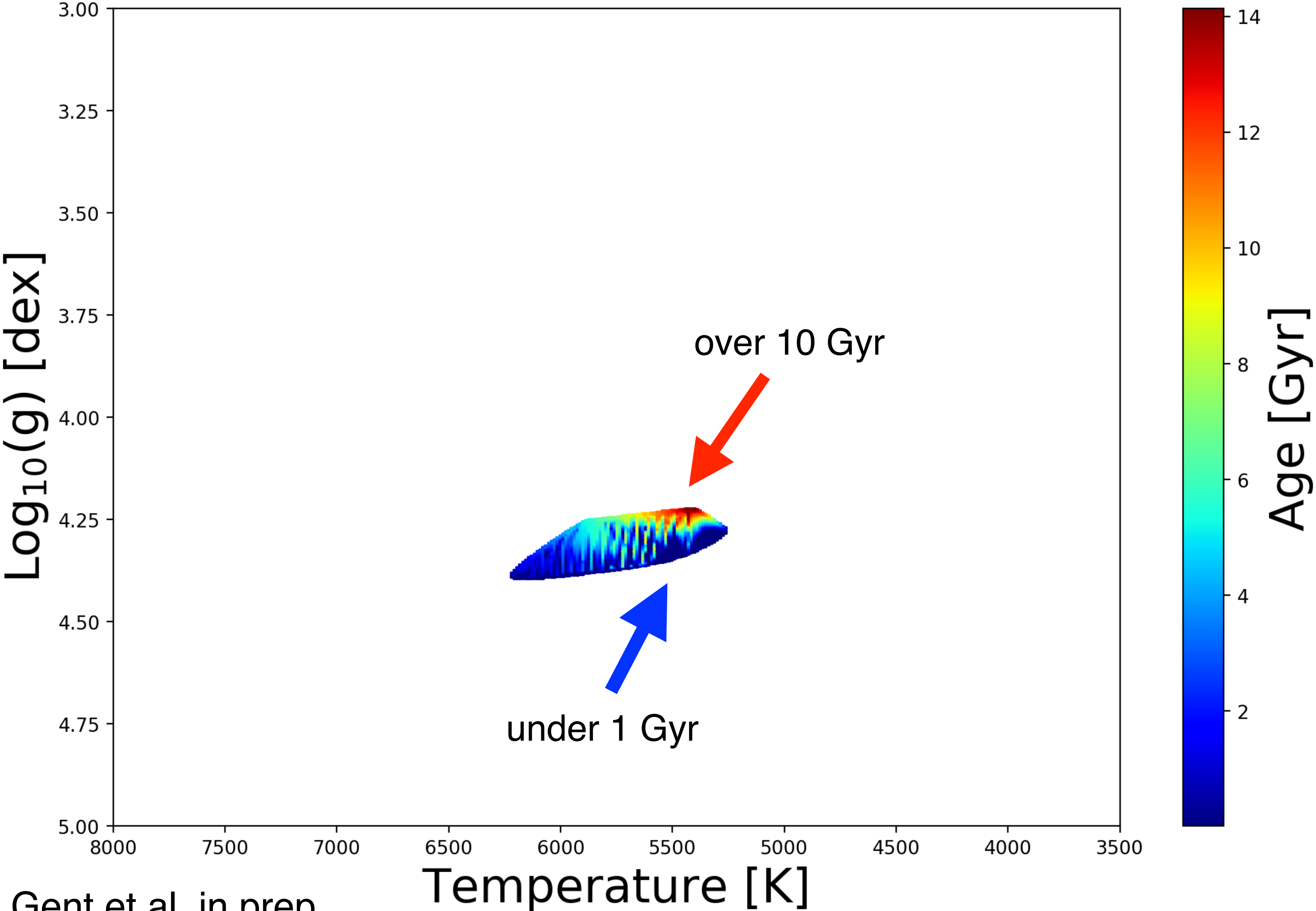
Gent et al. in prep



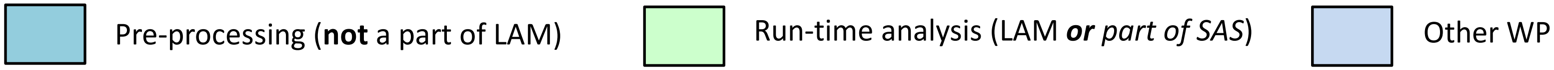
Gent et al. in prep

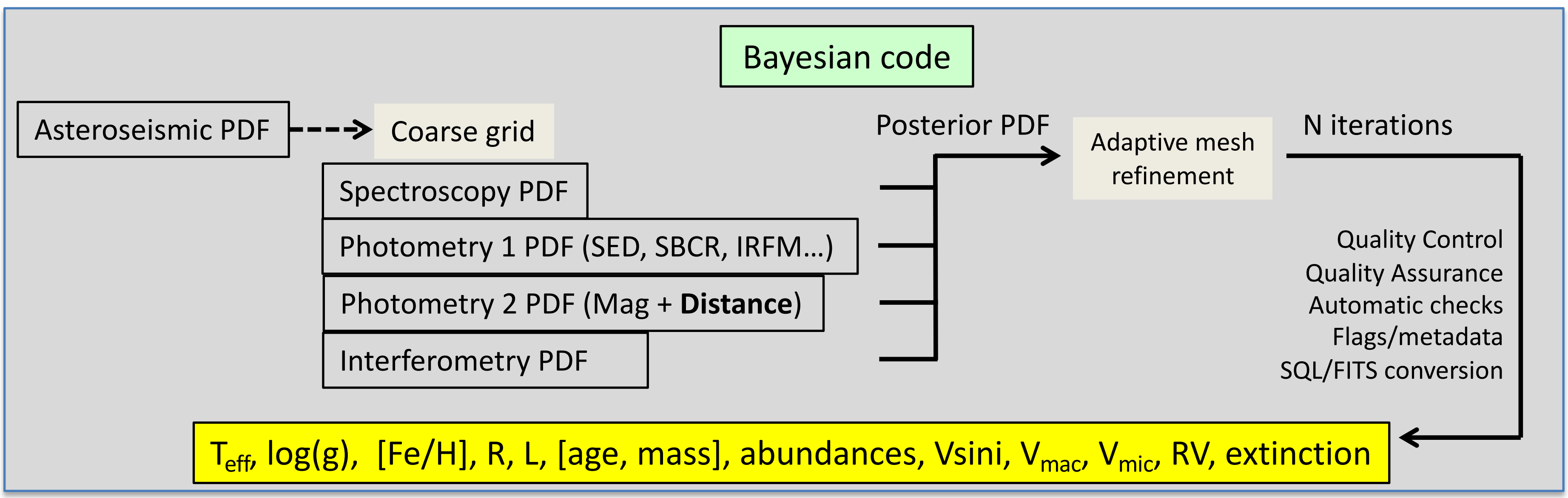


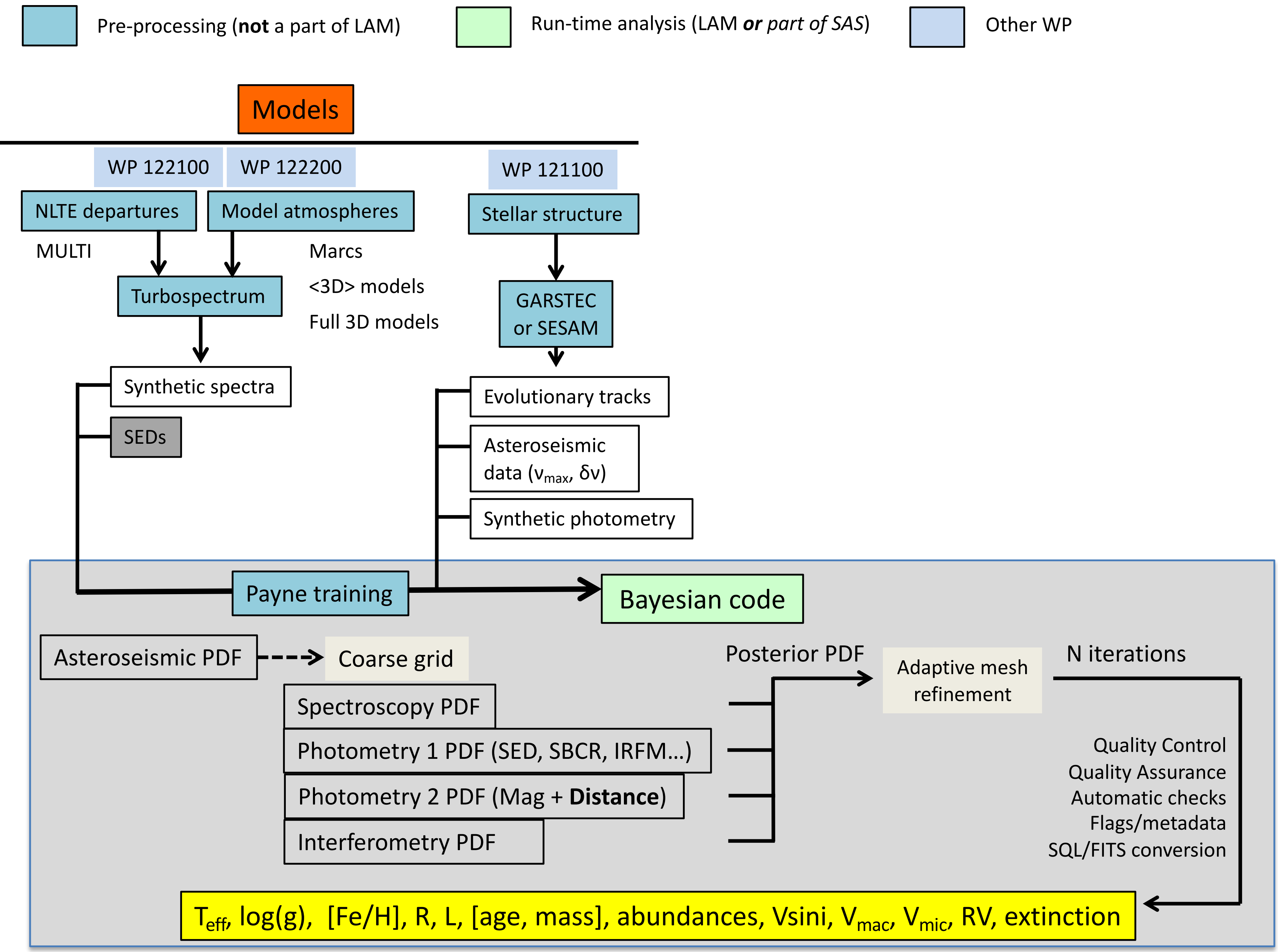
Gent et al. in prep



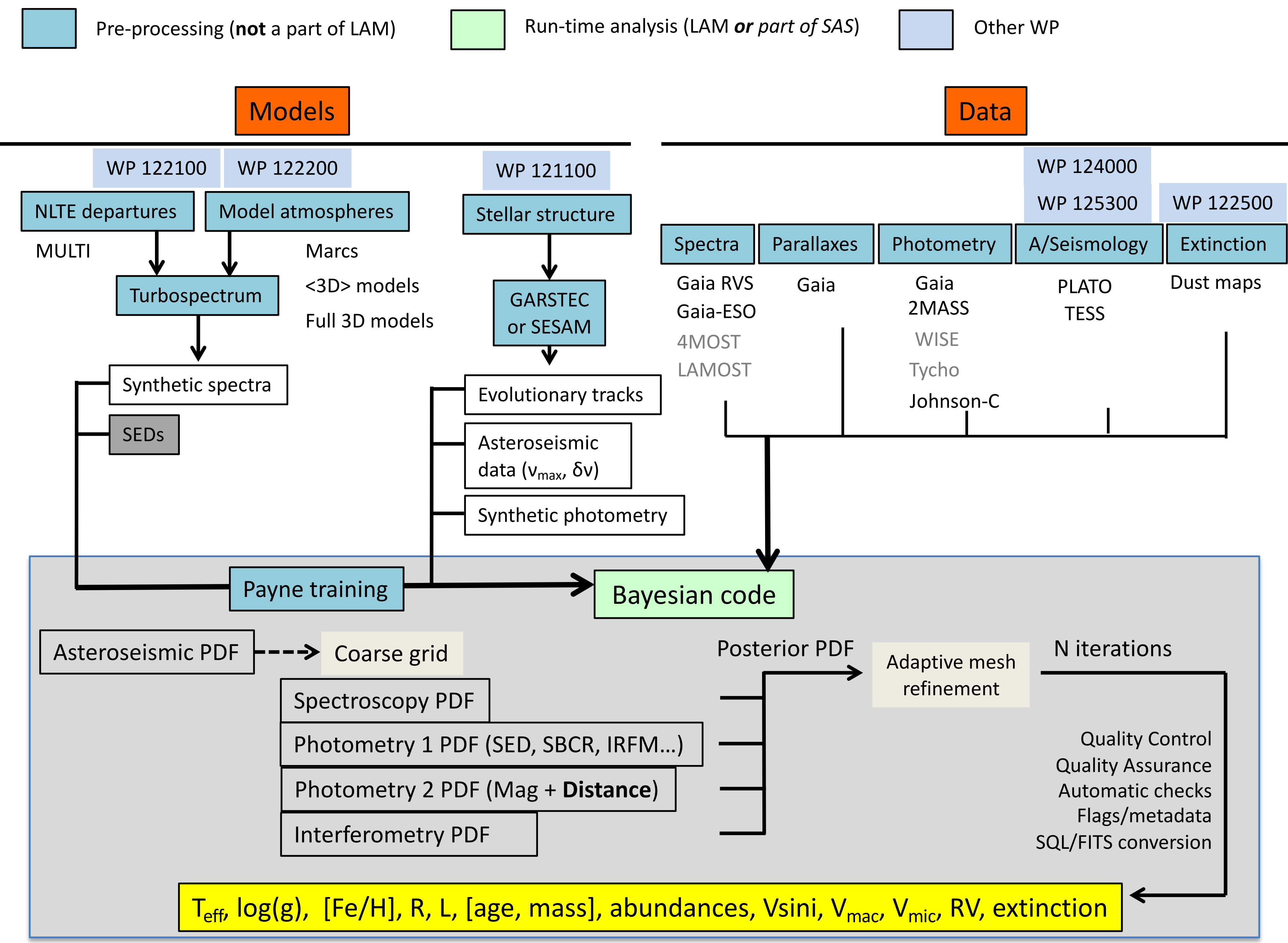
Gent et al. in prep


Pre-processing (**not** a part of LAM)
Run-time analysis (LAM ***or*** *part of SAS*)
Other WP


Bayesian code
Asteroseismic PDF
Coarse grid
Spectroscopy PDF
Photometry 1 PDF (SED, SBCR, IRFM…)
Photometry 2 PDF (Mag + **Distance**)
Interferometry PDF
Posterior PDF
Adaptive mesh refinement
N iterations
Quality Control
Quality Assurance
Automatic checks
Flags/metadata
SQL/FITS conversion
T_{eff}, log(g), [Fe/H], R, L, [age, mass], abundances, Vsini, V_{mac}, V_{mic}, RV, extinction



Pre-processing (**not** a part of LAM)
Run-time analysis (LAM ***or*** *part of SAS*)
Other WP
Models
WP 122100
WP 122200
WP 121100
NLTE departures
Model atmospheres
Stellar structure
MULTI
Marcs
<3D> models
Full 3D models
Turbospectrum
GARSTEC or SESAM
Synthetic spectra
SEDs
Evolutionary tracks
Asteroseismic data (ν_{max}, $\delta\nu$)
Synthetic photometry
Payne training
Bayesian code
Asteroseismic PDF
Coarse grid
Spectroscopy PDF
Photometry 1 PDF (SED, SBCR, IRFM…)
Photometry 2 PDF (Mag + **Distance**)
Interferometry PDF
Posterior PDF
Adaptive mesh refinement
N iterations
Quality Control
Quality Assurance
Automatic checks
Flags/metadata
SQL/FITS conversion
T_{eff}, log(g), [Fe/H], R, L, [age, mass], abundances, Vsini, V_{mac}, V_{mic}, RV, extinction



Pre-processing (**not** a part of LAM)
Run-time analysis (LAM ***or*** *part of SAS*)
Other WP
Models
Data
WP 122100
WP 122200
WP 121100
WP 124000
WP 125300
WP 122500
NLTE departures
Model atmospheres
Stellar structure
Spectra
Parallaxes
Photometry
A/Seismology
Extinction
MULTI
Marcs
<3D> models
Full 3D models
Turbospectrum
GARSTEC or SESAM
Gaia RVS
Gaia-ESO
4MOST
LAMOST
Gaia
Gaia
2MASS
WISE
Tycho
Johnson-C
PLATO
TESS
Dust maps
Synthetic spectra
SEDs
Evolutionary tracks
Asteroseismic data (ν_{max}, $\delta\nu$)
Synthetic photometry
Payne training
Bayesian code
Asteroseismic PDF
Coarse grid
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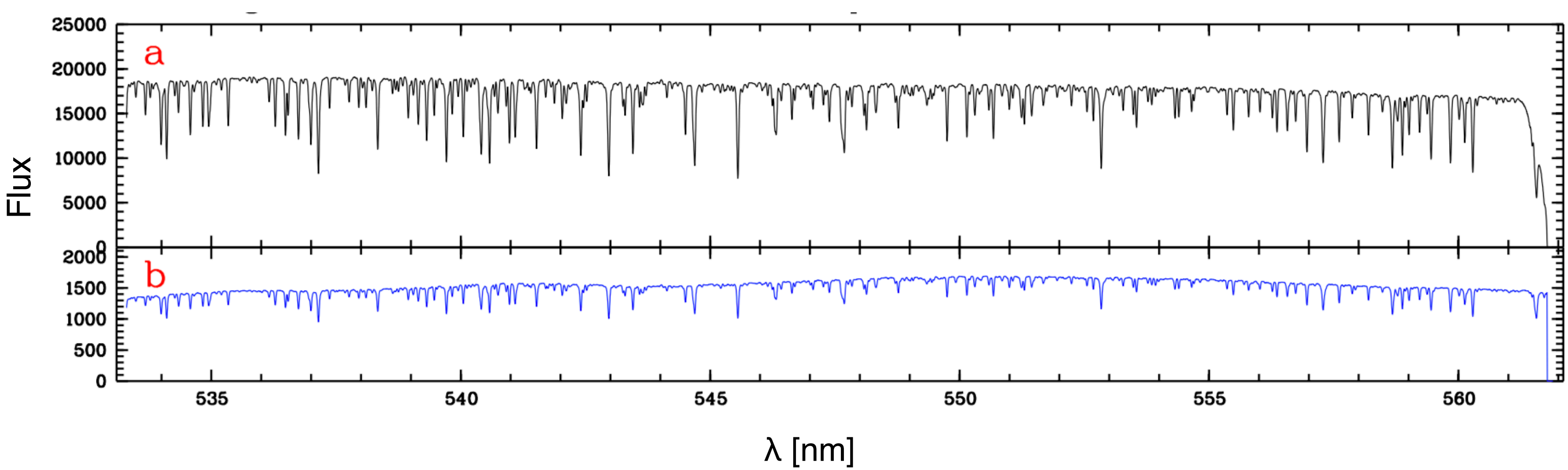
Photometry 1 PDF (SED, SBCR, IRFM…)
Photometry 2 PDF (Mag + **Distance**)
Interferometry PDF
Posterior PDF
Adaptive mesh refinement
N iterations
Quality Control
Quality Assurance
Automatic checks
Flags/metadata
SQL/FITS conversion
T_{eff}, log(g), [Fe/H], R, L, [age, mass], abundances, Vsini, V_{mac}, V_{mic}, RV, extinction

Pipeline v1.0

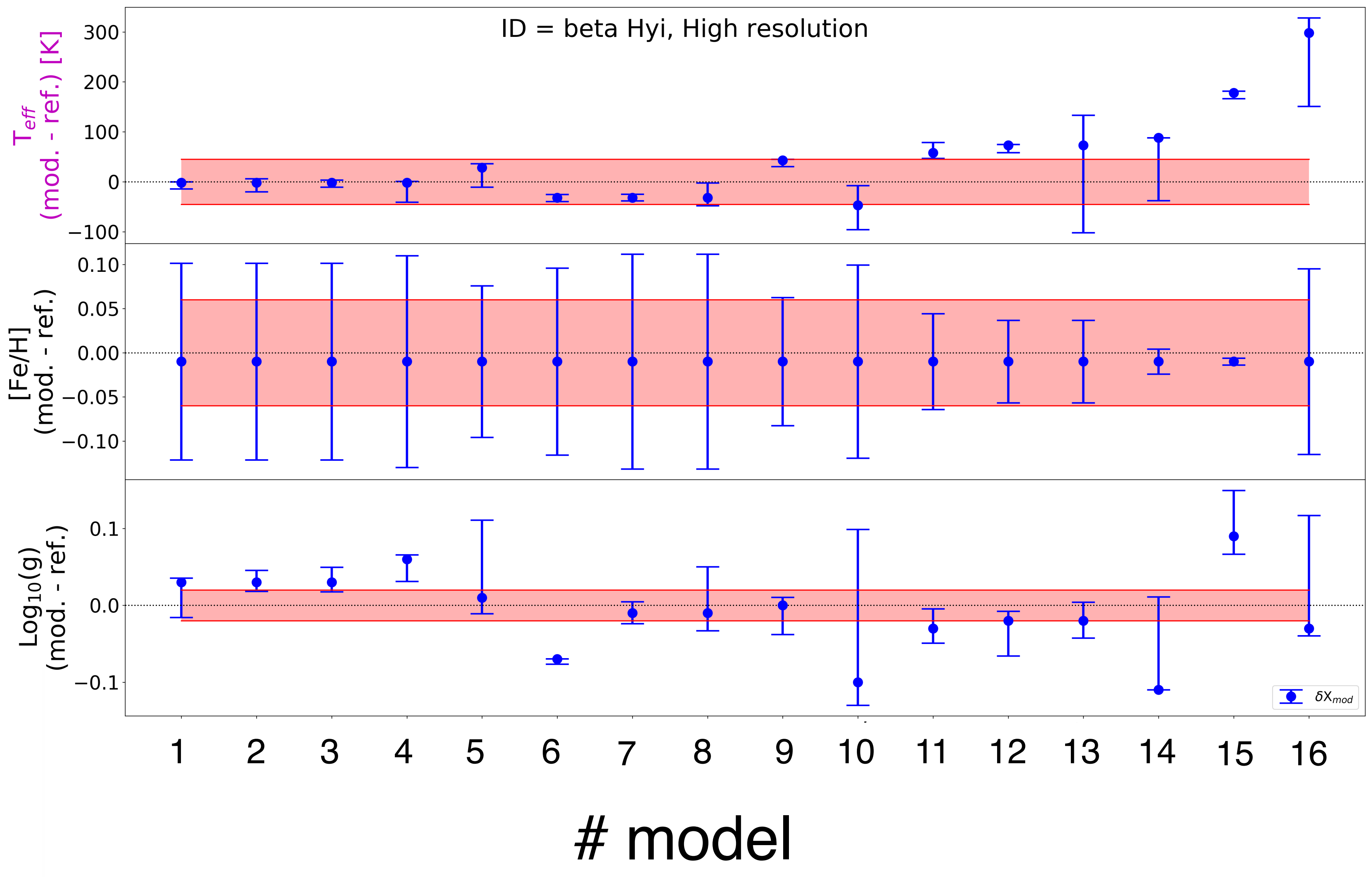
- Python source code of the full Bayesian analysis
- Models: Non-LTE synthetic spectra (AGSS09 Sun is NLTE); GARSTEC stellar evolution models
- Data: Observed spectra (Gaia-ESO: HR10), photometry (UBVRI, JHK, Gaia), parallaxes, asteroseismic data
- Parallelisation, runtime 5 - 30 minutes/star

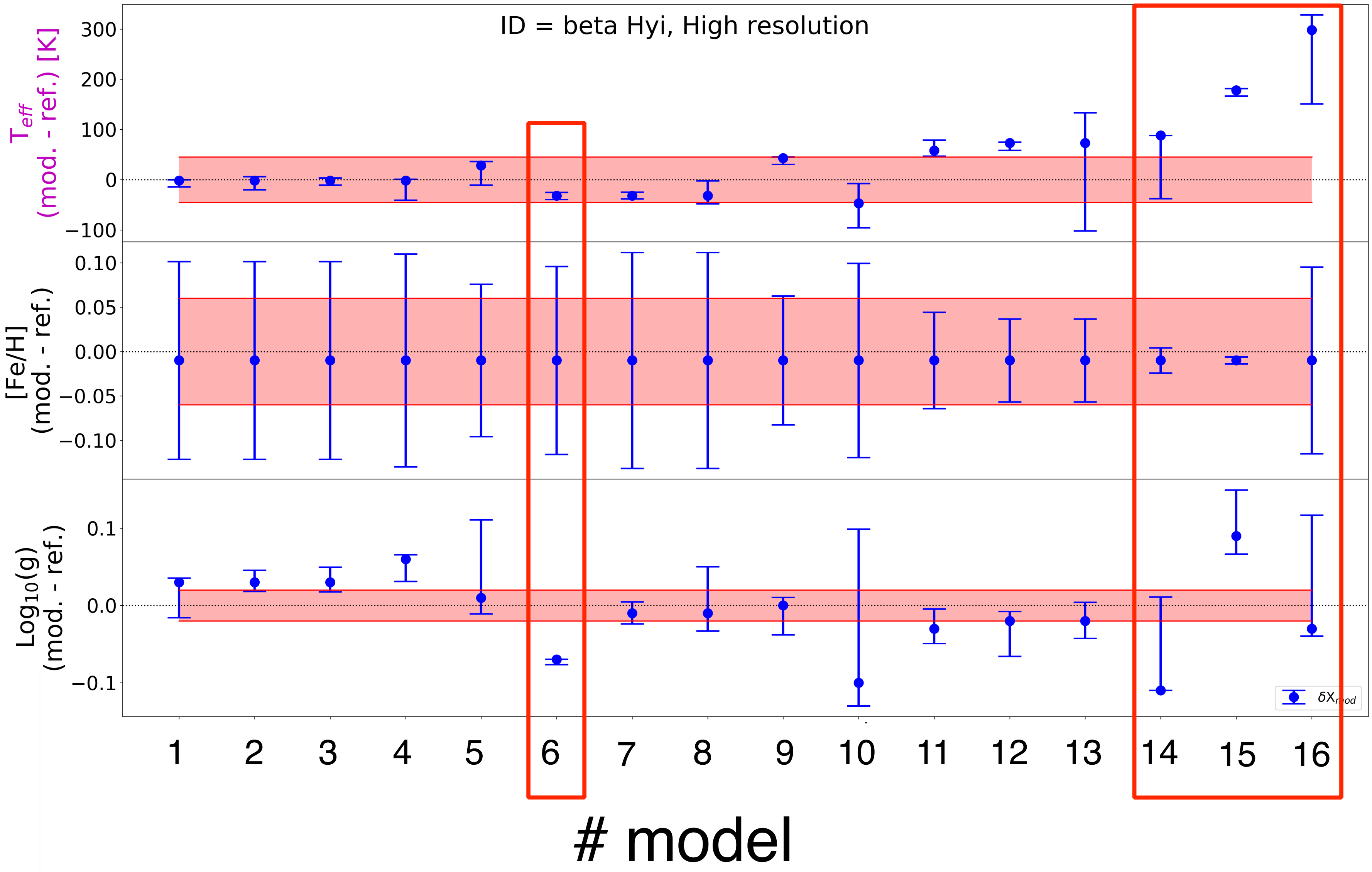


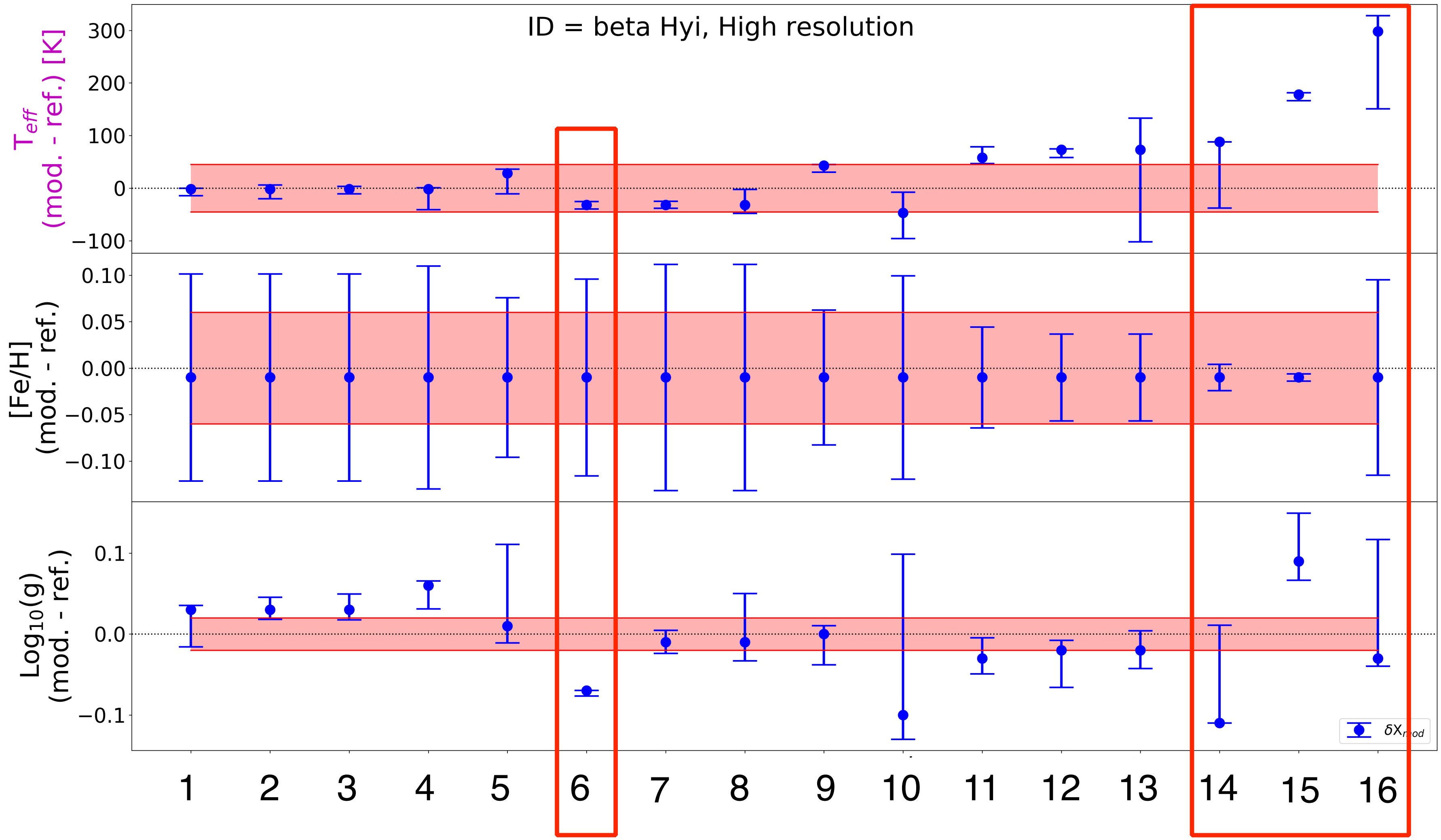
First results for PLATO/Gaia benchmark stars

Reference parameters based on:
- interferometry (Teff)
- asteroseismology (logg)
- Non-LTE analysis of very high-resolution spectra (HARPS, NARVAL, UVES)

Heiter+2015; Jofre+2014, 2015; Lundkvist+2014; Sahlholdt+2019


ID = beta Hyi, High resolution
T_eff (mod. - ref.) [K]
300
200
100
0
−100
[Fe/H] (mod. - ref.)
0.10
0.05
0.00
−0.05
−0.10
Log10(g) (mod. - ref.)
0.1
0.0
−0.1
δX_mod
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
model


ID = beta Hyi, High resolution
T_eff (mod. - ref.) [K]
300
200
100
0
−100
[Fe/H] (mod. - ref.)
0.10
0.05
0.00
−0.05
−0.10
Log10(g) (mod. - ref.)
0.1
0.0
−0.1
δX_mod
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
model

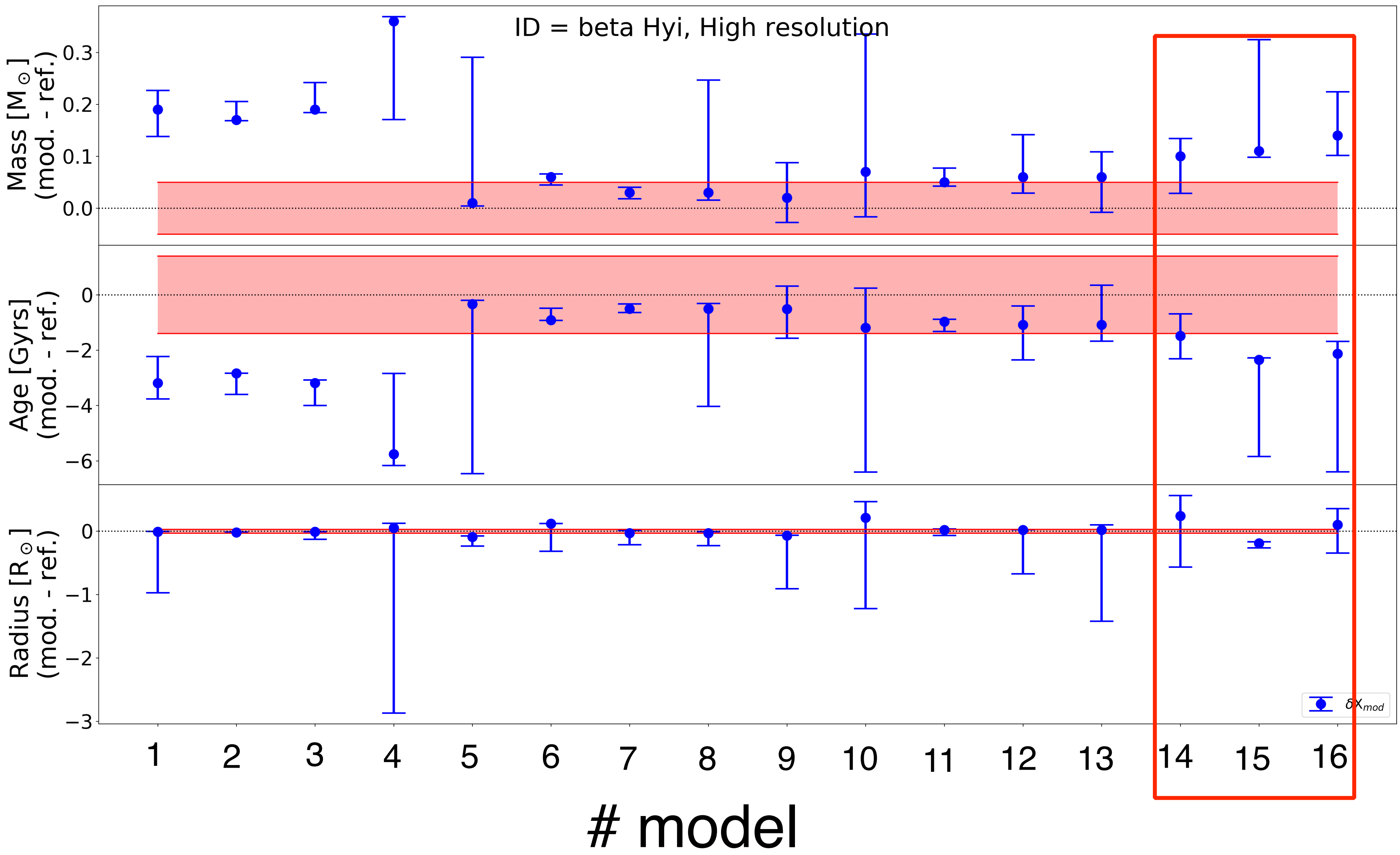


6 Combined PDF: no asteroseismology

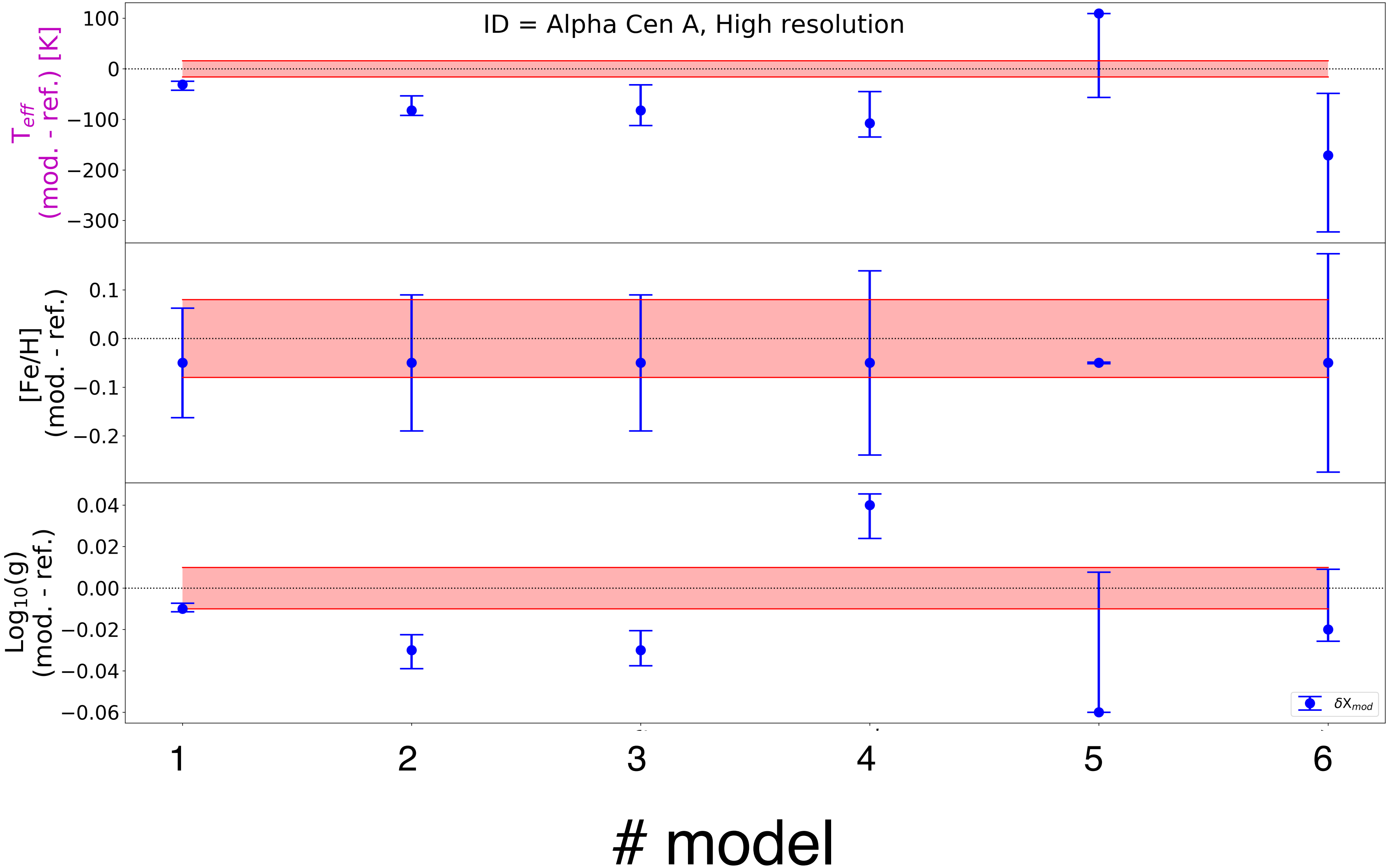
14 Spectroscopy

15 Combined PDF: Gaia, no asteroseismology

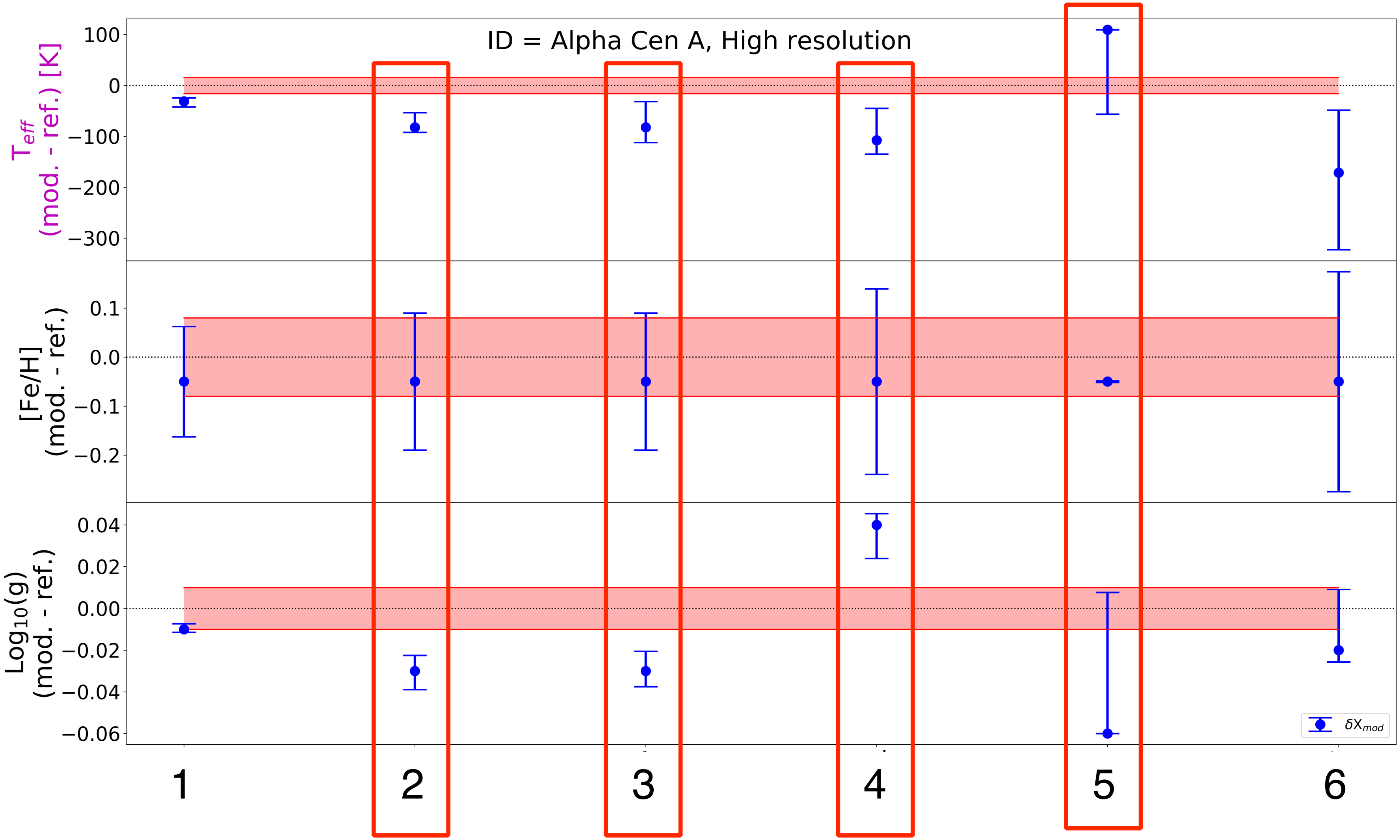
16 Photometry: Gaia only



ID = beta Hyi, High resolution
Mass [M$_\odot$] (mod. - ref.)
0.3
0.2
0.1
0.0
Age [Gyrs] (mod. - ref.)
0
−2
−4
−6
Radius [R$_\odot$] (mod. - ref.)
0
−1
−2
−3
δx_{mod}
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
model



ID = Alpha Cen A, High resolution
T_eff (mod. - ref.) [K]
100
0
−100
−200
−300
[Fe/H] (mod. - ref.)
0.1
0.0
−0.1
−0.2
Log10(g) (mod. - ref.)
0.04
0.02
0.00
−0.02
−0.04
−0.06
δX_mod
1
2
3
4
5
6
model

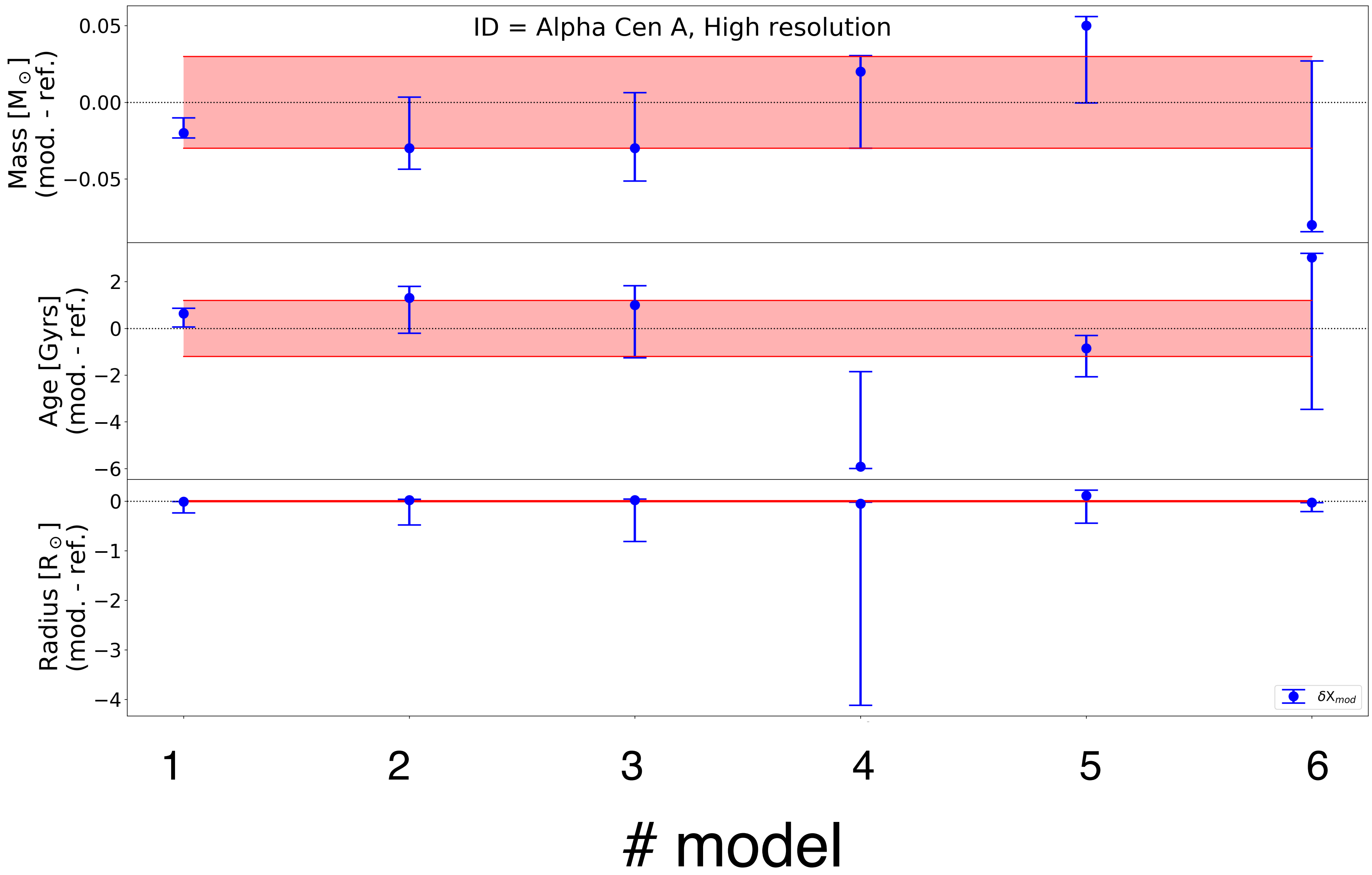


2 Combined PDF: no asteroseismology

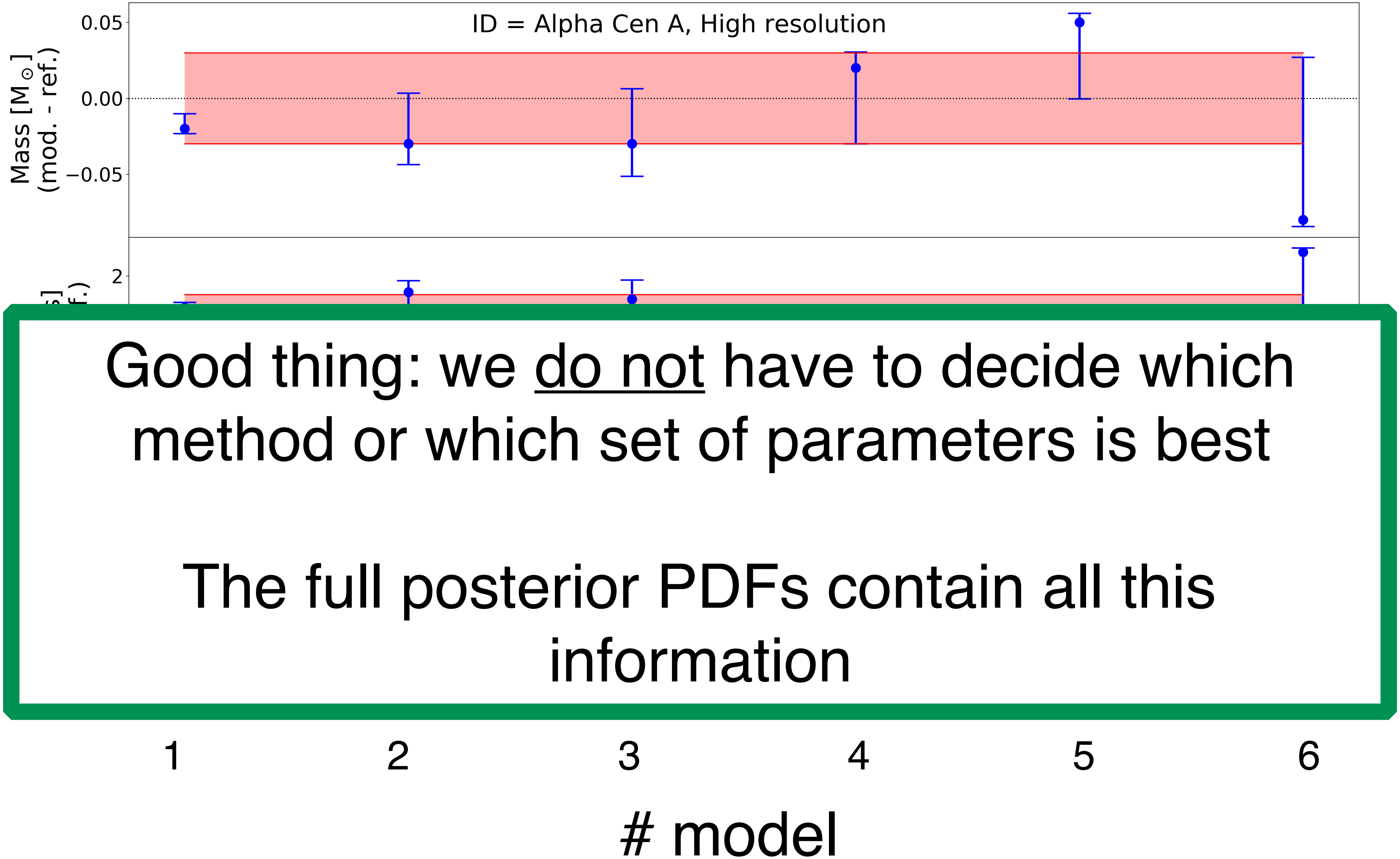
3 Photometry + parallax

4 Photometry (colour)

5 Spectroscopy



ID = Alpha Cen A, High resolution
Mass [M$_\odot$] (mod. - ref.)
0.05
0.00
−0.05
Age [Gyrs] (mod. - ref.)
2
0
−2
−4
−6
Radius [R$_\odot$] (mod. - ref.)
0
−1
−2
−3
−4
δX_{mod}
1
2
3
4
5
6
model



Good thing: we do not have to decide which method or which set of parameters is best

The full posterior PDFs contain all this information

Pipeline v1.0: results

T_{eff}

ID	reference			WP122300 pipeline		
	T_{eff}	log(g)	[Fe/H]	T_{eff}	log(g)	[Fe/H]
α Cen A	5792 ± 16	4.31 ± 0.01	0.26 ± 0.08	5760^{+7}_{-11}	$4.30^{+0.01}_{-0.01}$	0.21
bet Hyi	5873 ± 45	3.98 ± 0.02	-0.04 ± 0.06	5871^{+2}_{-15}	$4.01^{+0.01}_{-0.05}$	-0.05
bet Vir	6083 ± 41	4.10 ± 0.02	0.24 ± 0.07	6132^{+6}_{-9}	$4.09^{+0.02}_{-0.01}$	0.23
eta Boo	6099 ± 28	3.79 ± 0.02	0.32 ± 0.08	6139^{+10}_{-18}	$3.84^{+0.02}_{-0.01}$	0.31

Pipeline v1.0: results

[Fe/H]

ID	reference			WP122300 pipeline		
	$T_{\rm eff}$	log(g)	[Fe/H]	$T_{\rm eff}$	log(g)	[Fe/H]
α Cen A	5792 ±16	4.31 ±0.01	0.26 ±0.08	5760^{+7}_{-11}	$4.30^{+0.01}_{-0.01}$	0.21
bet Hyi	5873 ±45	3.98 ±0.02	-0.04 ±0.06	5871^{+2}_{-15}	$4.01^{+0.01}_{-0.05}$	-0.05
bet Vir	6083 ±41	4.10 ±0.02	0.24 ±0.07	6132^{+6}_{-9}	$4.09^{+0.02}_{-0.01}$	0.23
eta Boo	6099 ±28	3.79 ±0.02	0.32 ±0.08	6139^{+10}_{-18}	$3.84^{+0.02}_{-0.01}$	0.31

WP122300: immediate steps

- include IRFM, SBCR, interferometry
- test on spectra of other benchmark stars
  - priority targets tbd (with WP125500)
  - high-resolution spectra: HARPS (archival data)
  - medium-res spectra: Gaia-ESO (FGK,~10 M dwarfs) and Gaia-ESO degraded to Gaia RVS (all benchmarks), IR spectra
- performance can be improved
- update N of chemical elements in synthetic grids => detailed elemental abundances (Li, CNO, Mg, Si ..)

WP122300: summary

First version of the Bayesian pipeline

- **consistent and objective statistical analysis** in the multi-D parameter space: T_{eff}, logg, [Fe/H], [Mg/H], also M, τ, R
- combination of spectra, asteroseismology, photometry, parallaxes
- full PDFs for the core parameter space available
- implementation of other modules (SBCR, interferometry, SED..), other chemical elements in progress

WP122300: summary

Important results

- no need for high-res spectra: R~20,000 sufficient (lower R, λ coverage to be tested)
- **Gaia** photometry produces **erroneous** T_{eff} estimates
- Better constraints with 2MASS + parallax + V mag
- **Asteroseismic** data (d_nu, n_max) **improve log(g)** => help to break degeneracies in spectroscopy and greately confine the photometric parameter space

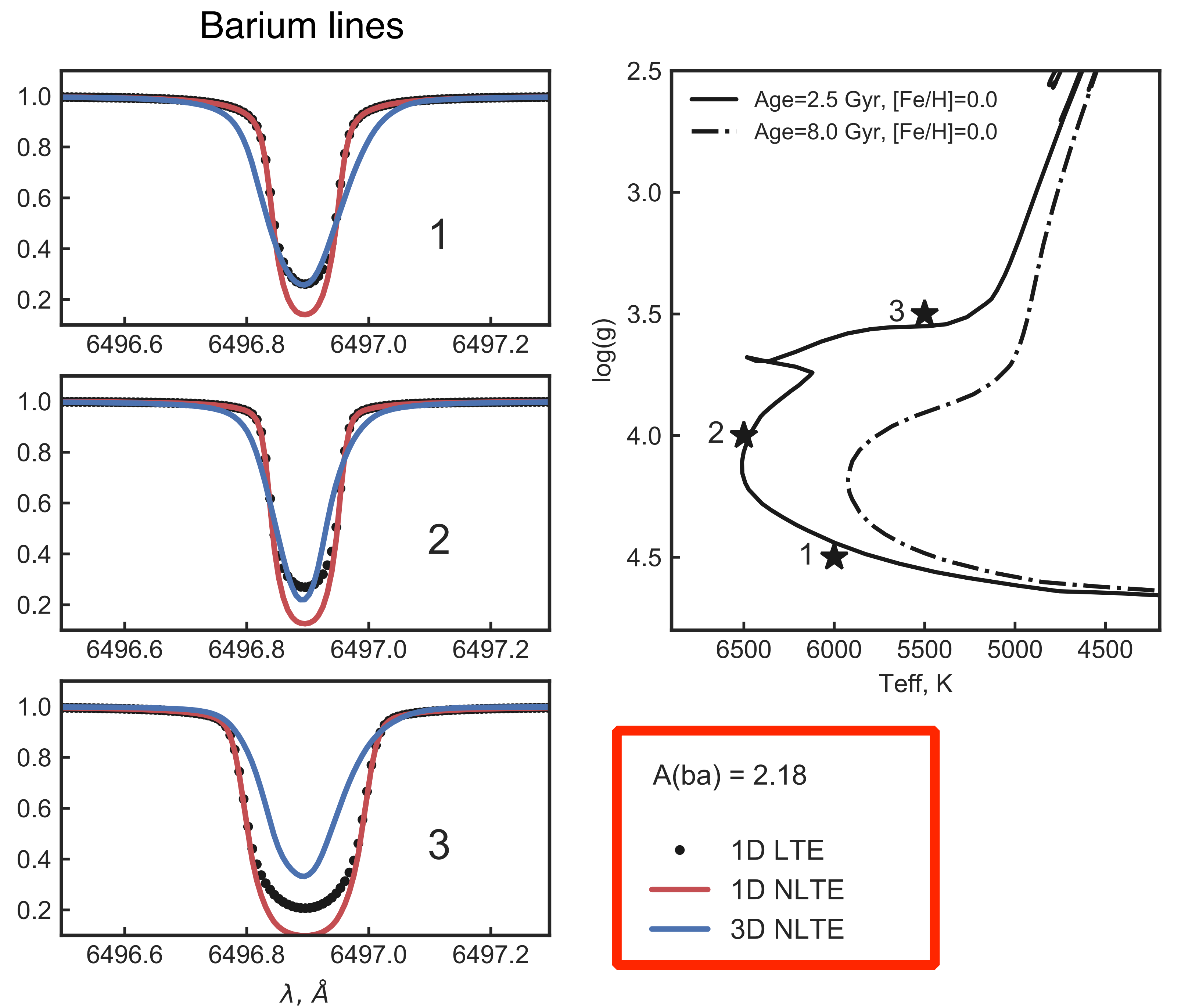
=> T_{eff} and metallicities **accurate** to < 1%

WP122300: open questions

- ➡ <u>Observed stellar specta</u>
  - instruments? (Gaia RVS): typical λ coverage, resolution
  - continuum normalisation?
  - which chemical elements are priority? (linelist)
- ➡ <u>Activity diagnostics</u>
  - flagging lines sensitive to activity?
  - EWs measurements? are there fully automated EW Python modules?
- ➡ <u>SED fitting and Interferometry</u>
  - source of SED (type of data e.g, SPHEREx) and F_{bol}?
- ➡ <u>Stellar models</u>
  - GARSTEC or SESTAM? discretisation, coverage
- ➡ <u>Benchmark stars</u>
  - what are the main selection criteria?
  - how many stars are needed for definitive statements?

Interface with other WPs

- ➡ Model spectra: WP 122100 and WP122200 (1D and 3D models, non-LTE)
- ➡ Fundamental stellar parameters:
  - WP122300 ‘Fundamental stellar parameters’
  - WP125200 ‘Incorporating Classical Parameters’
- ➡ Spectroscopy:
  - WP 146 'Spectroscopy'
    - WP 146200 ‘Tools for Spectral Classification’
    - WP 146300 ‘Infrared Spectroscopy’
- ➡ Activity from spectra:
  - WP146100 ‘Activity indicators and Doppler information on Active stars’
  - WP123000 ‘Stellar Activity and Rotation’
- ➡ Assembly and pre-processing of observed spectra (e.g. continuum, RV)
  - WP 146 ‘Spectroscopy’ - only small sample
  - WP 35 / 37 (‘Preparatory data’, ‘PIC’)


Barium lines
1
2
3
λ, Å
log(g)
Teff, K
Age=2.5 Gyr, [Fe/H]=0.0
Age=8.0 Gyr, [Fe/H]=0.0
A(ba) = 2.18
1D LTE
1D NLTE
3D NLTE

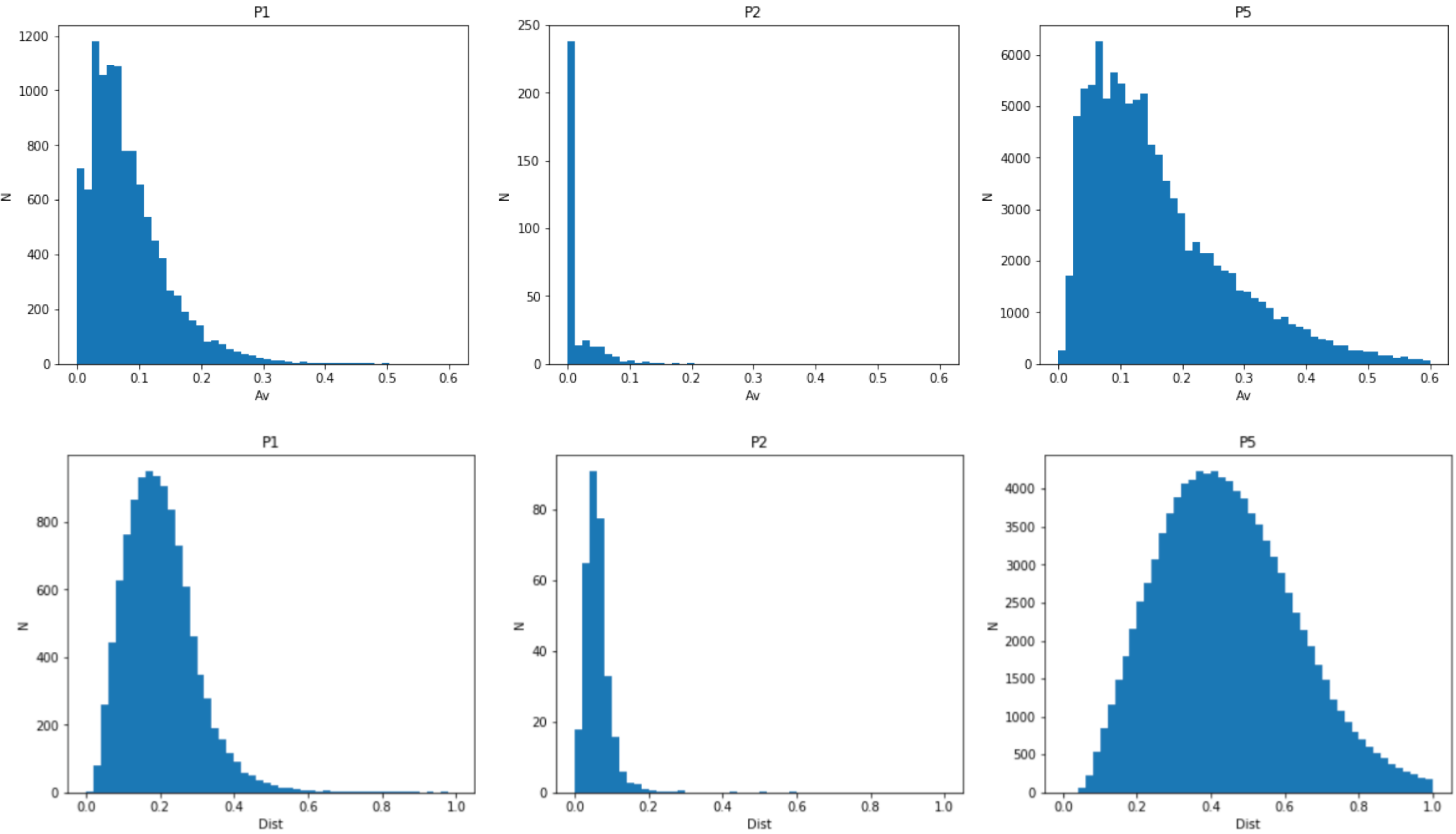
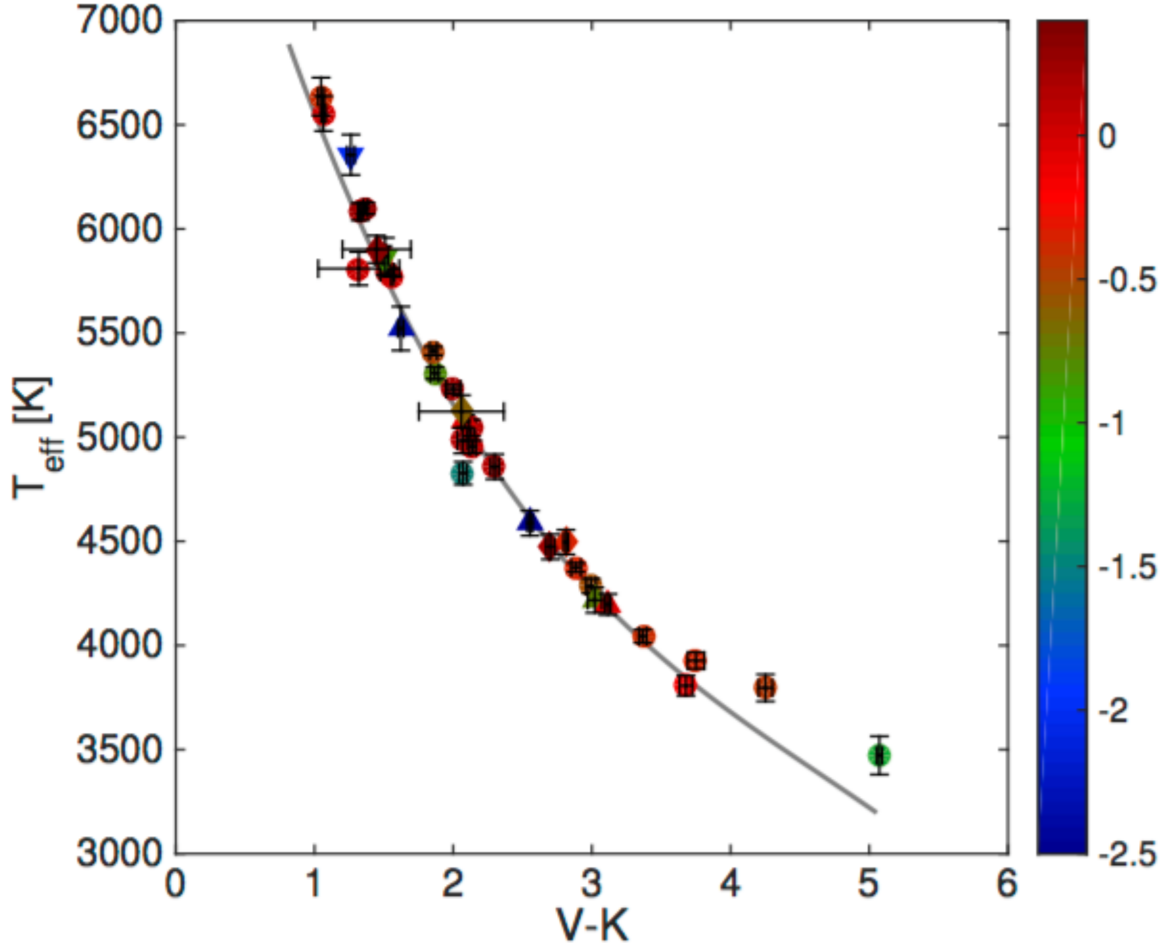
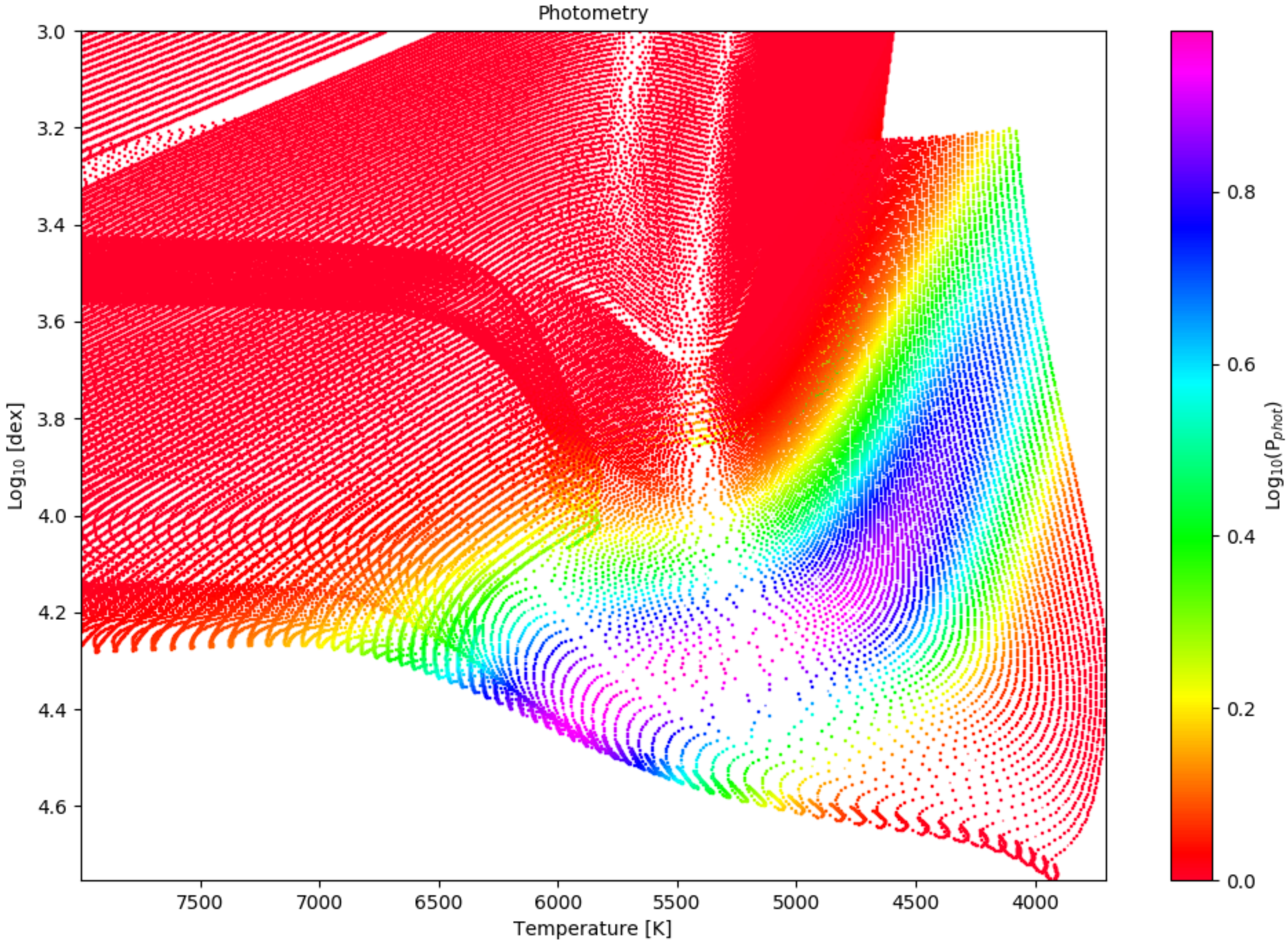
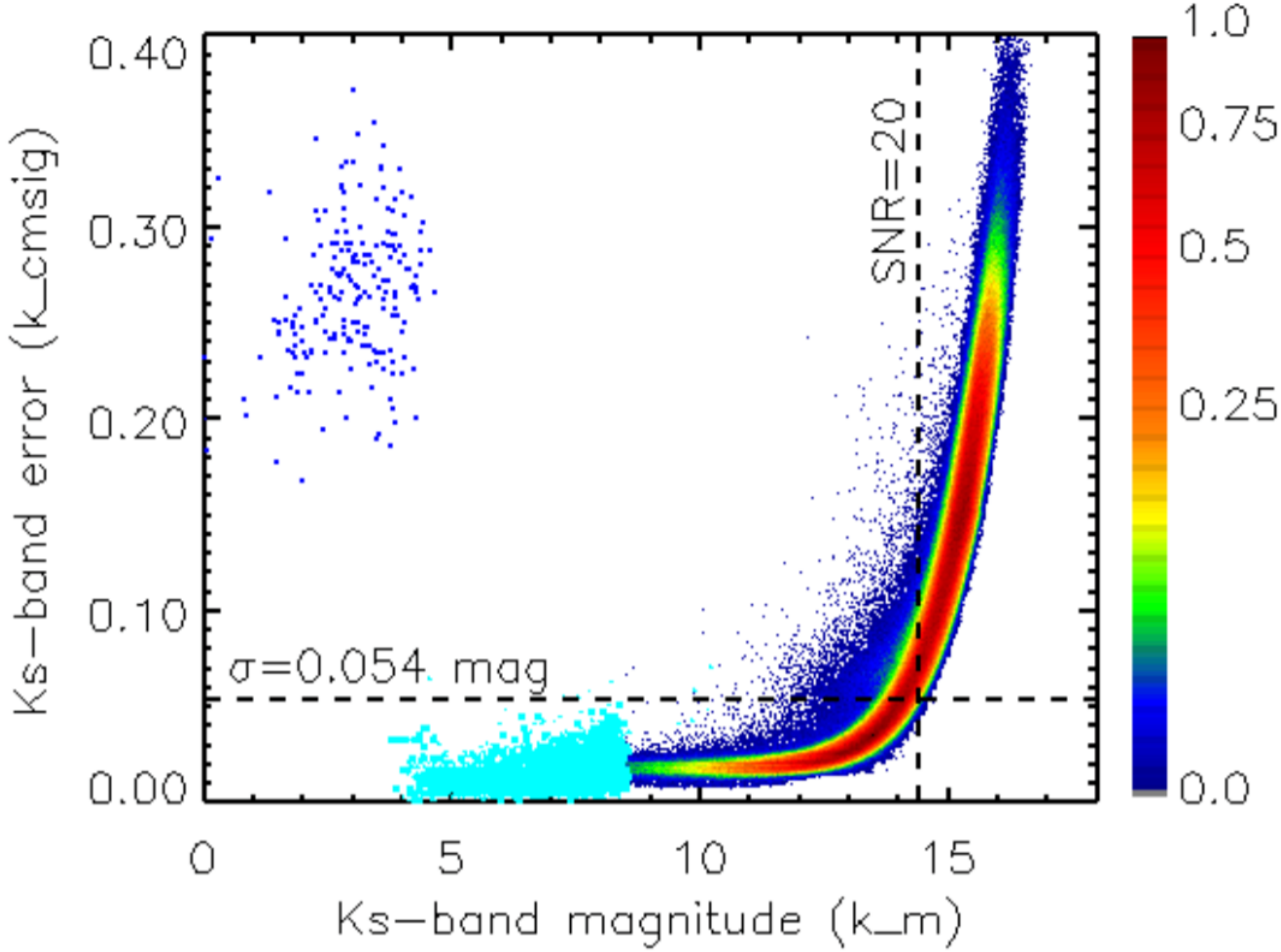


Figure 5: *Distance to stars (in kpc) in each of the PLATO samples P1 (left), P2 (middle) and P5 (right).*

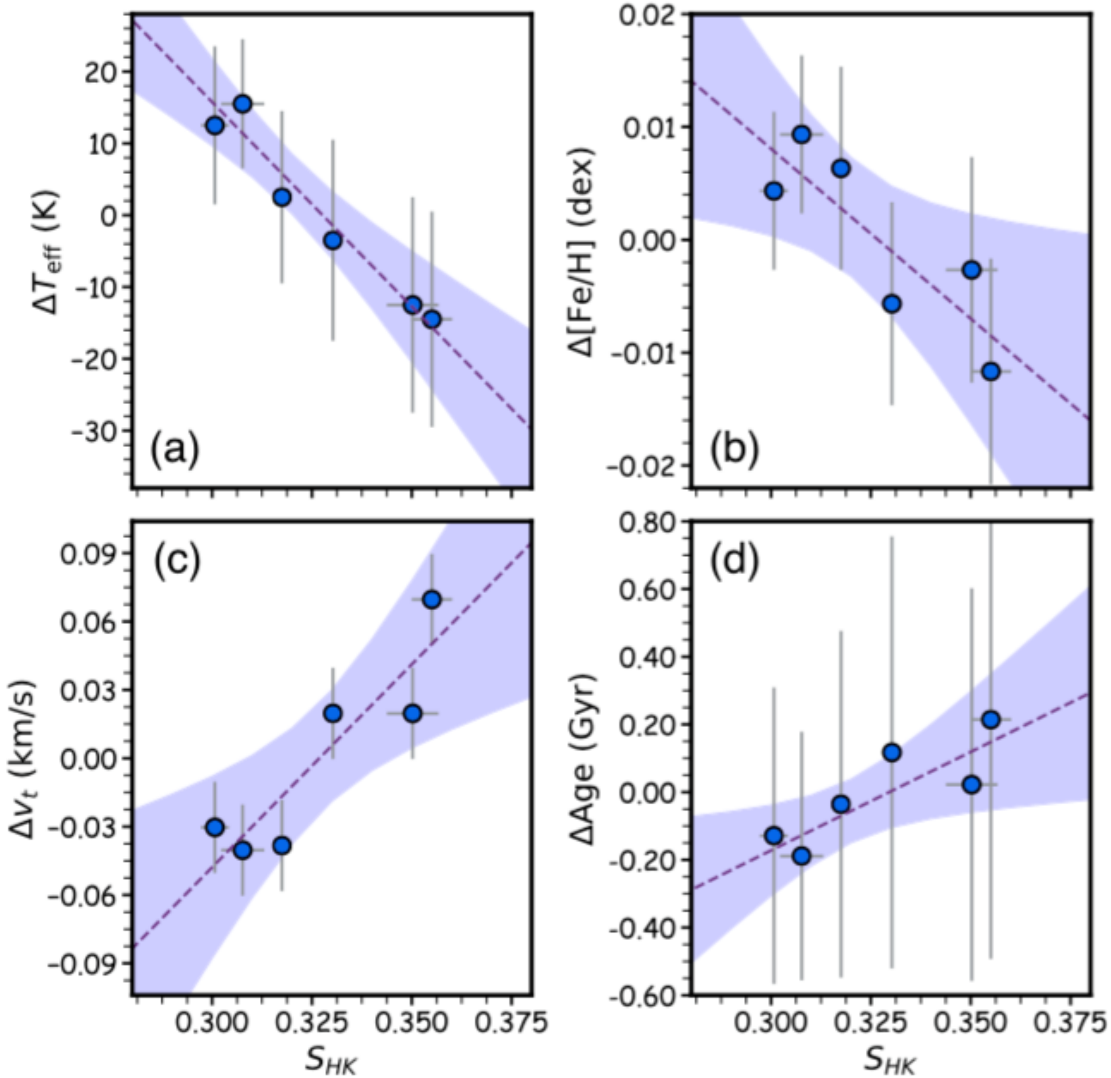


Heiter et al. 2015


Photometry
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
Log10 [dex]
7500
7000
6500
6000
5500
5000
4500
4000
Temperature [K]
0.0
0.2
0.4
0.6
0.8
Log10(P_phot)



Casagrande & Gonzales Hernandez



Galarza et al. 2019