Stellar populations model developments

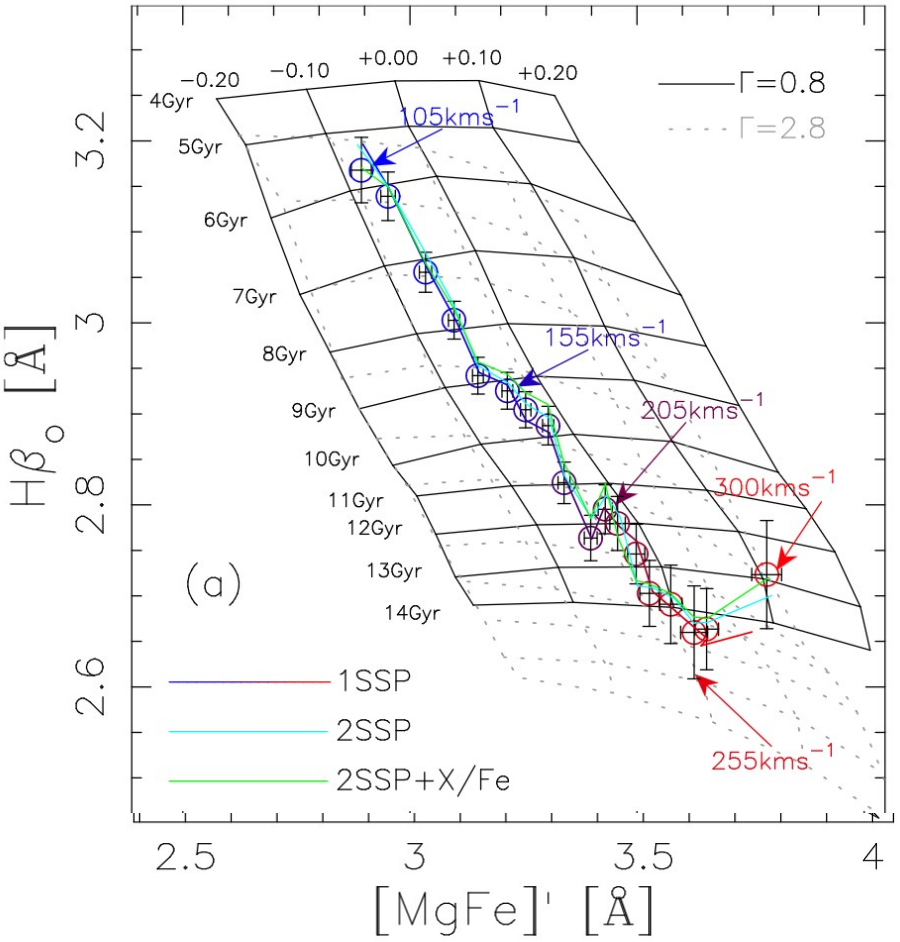
Alexandre Vazdekis

21/11/2024, Paraty, Brazil

IAU Symposium 395: Stellar populations in the Milky Way and beyond

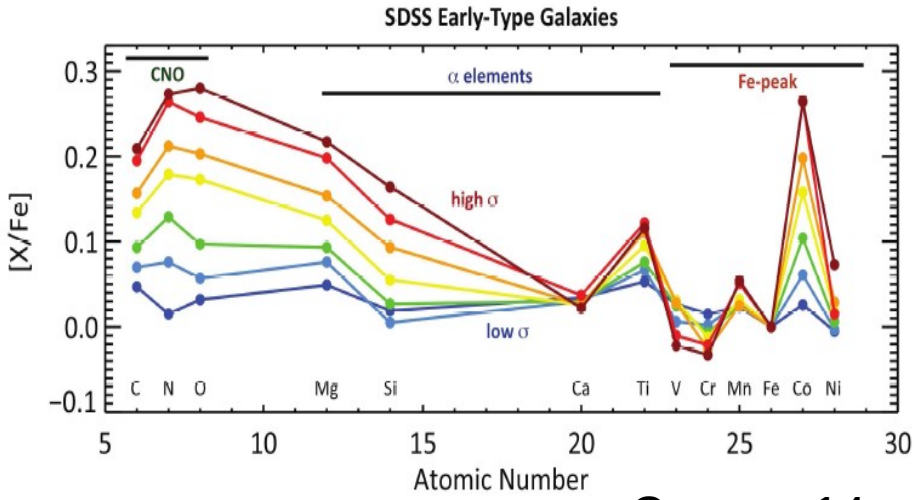
An event sponsored by the IAU | November 17-22, 2024

Stellar populations of ETGs



La Barbera+13

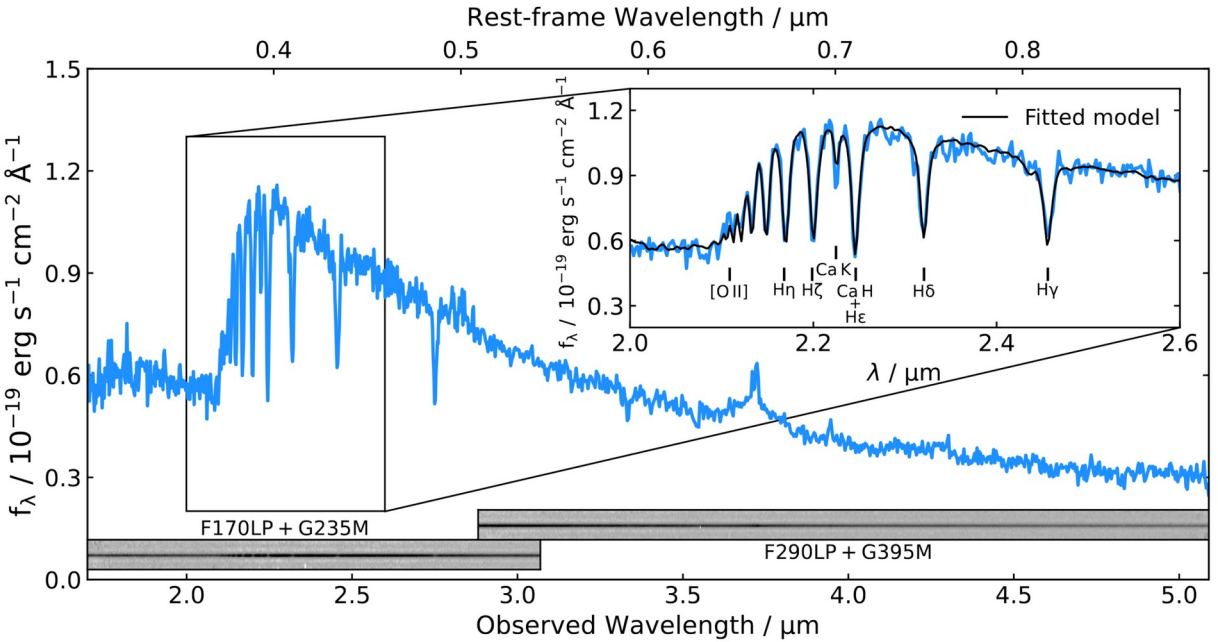
Increasing age, metallicity and abundance ratios as a function of galaxy mass. Early & fast formation



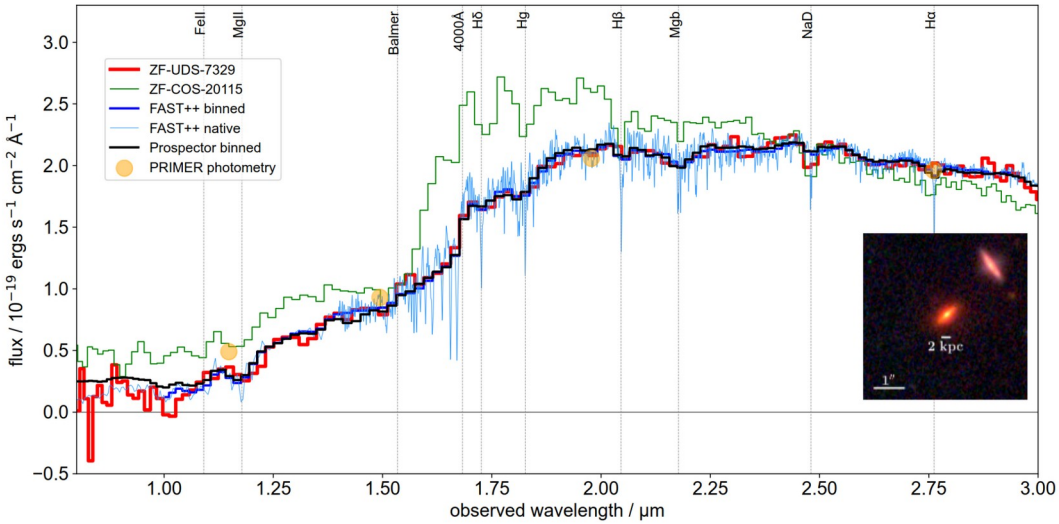
Conroy+14

Very early formation epoch

JWST observations:
massive (>10^{11}Mo)
quiescent galaxies
at z>3 (formation
epoch: z~11)



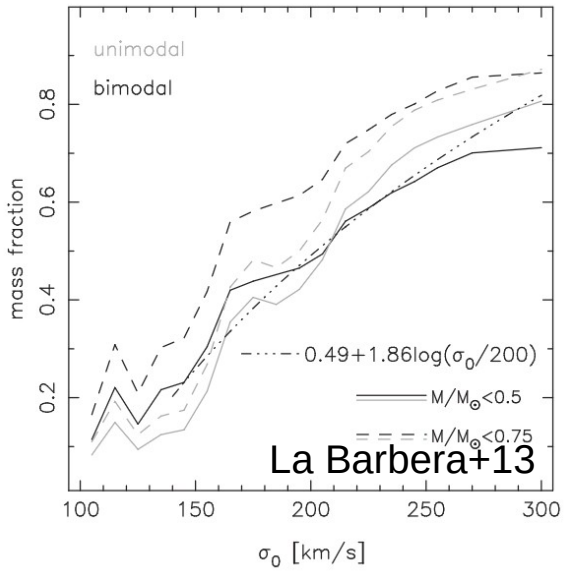
Carnall+23 (z=4.7)

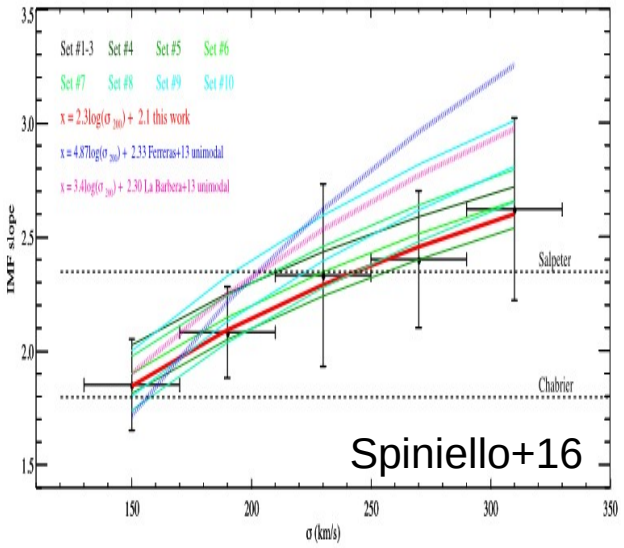


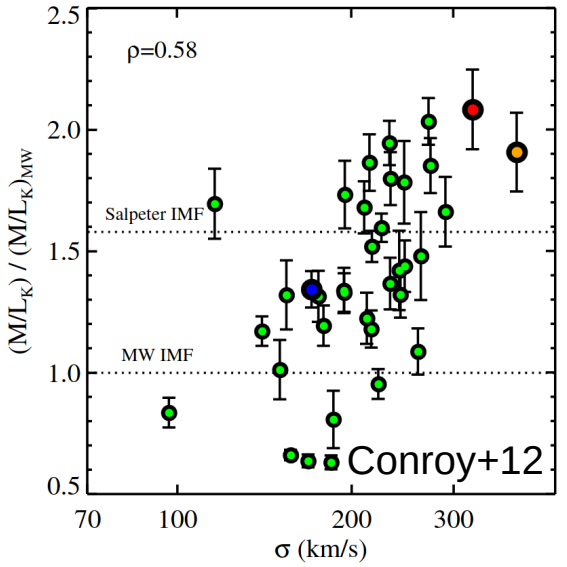
Glazebrook+24 (z=3.2)

IMF variations:

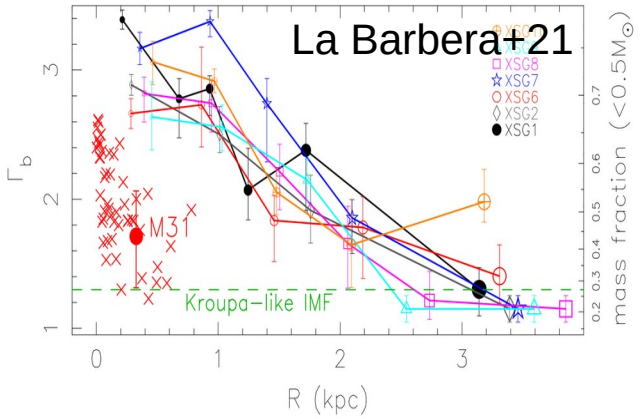
With galaxy mass:

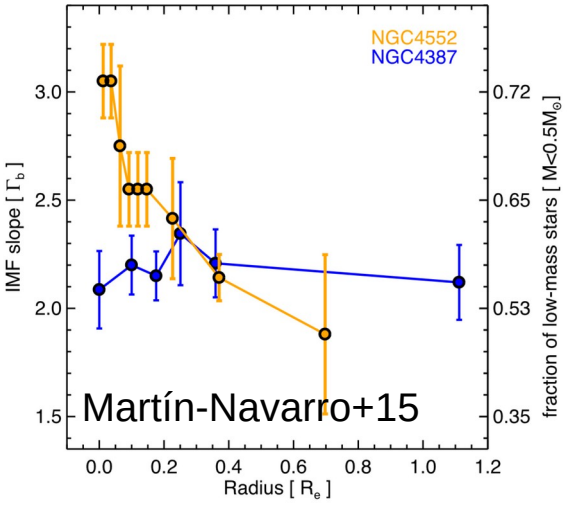


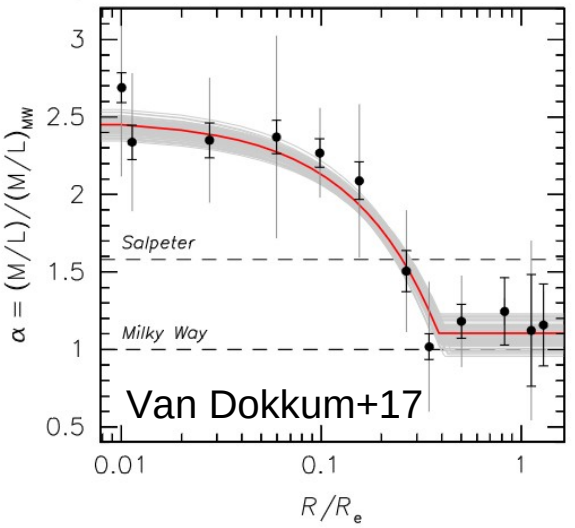




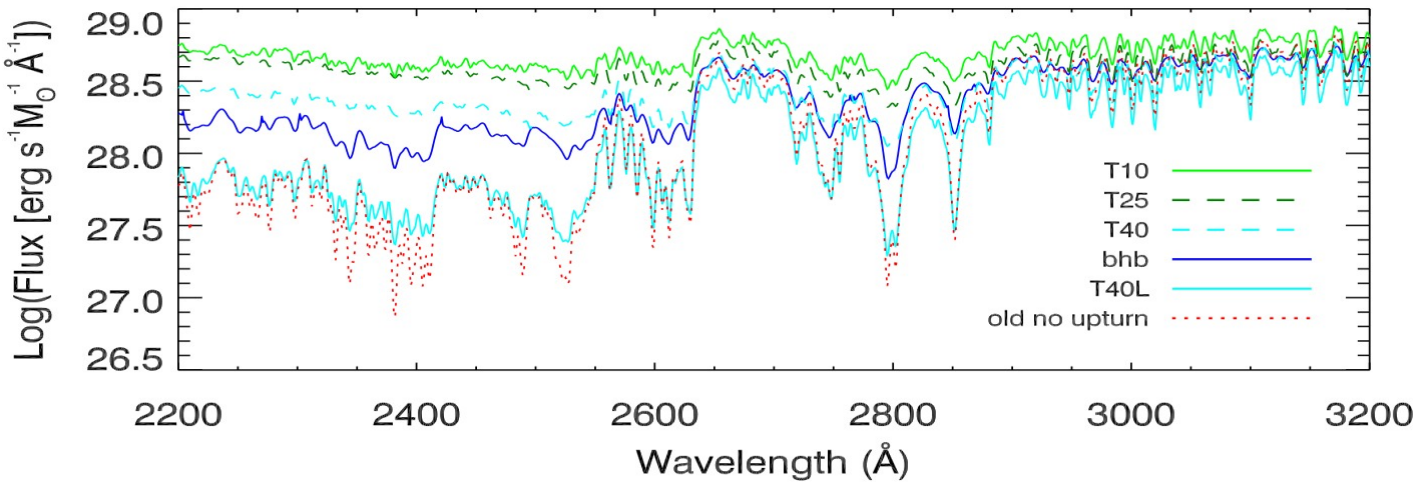
Within galaxies:





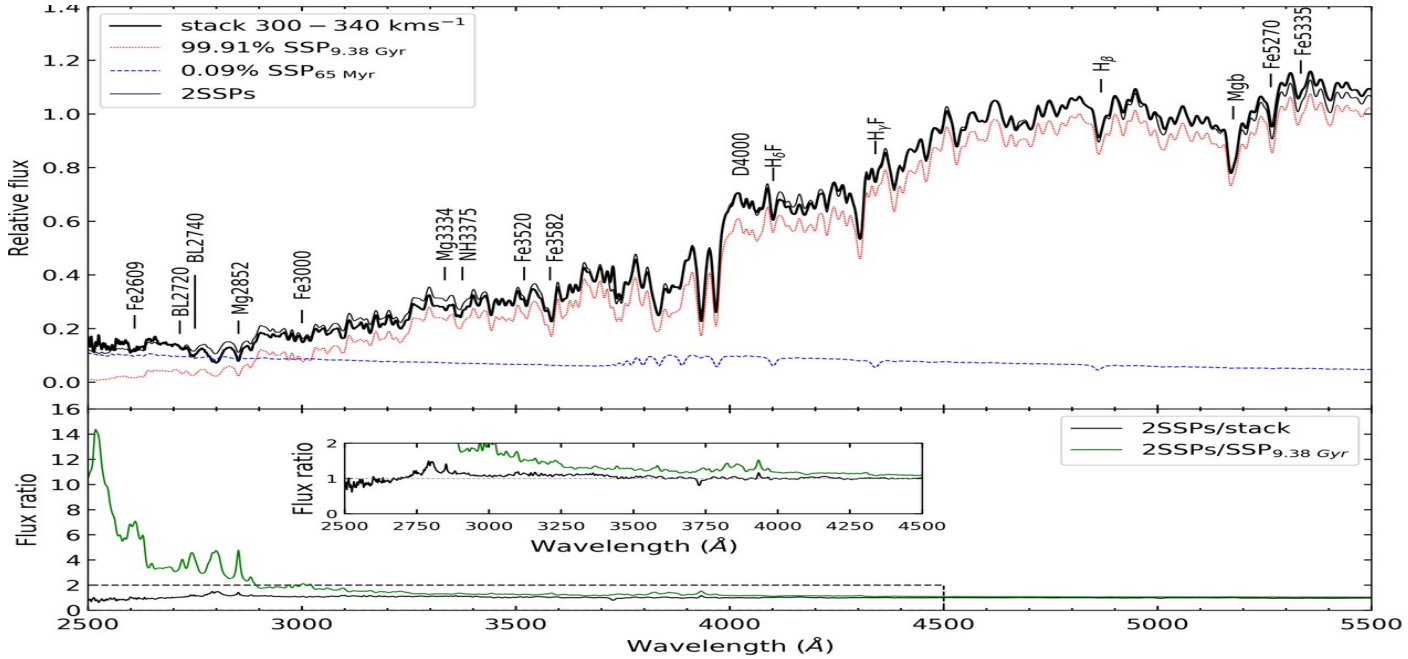


Opening the UV window:



Old contributions:

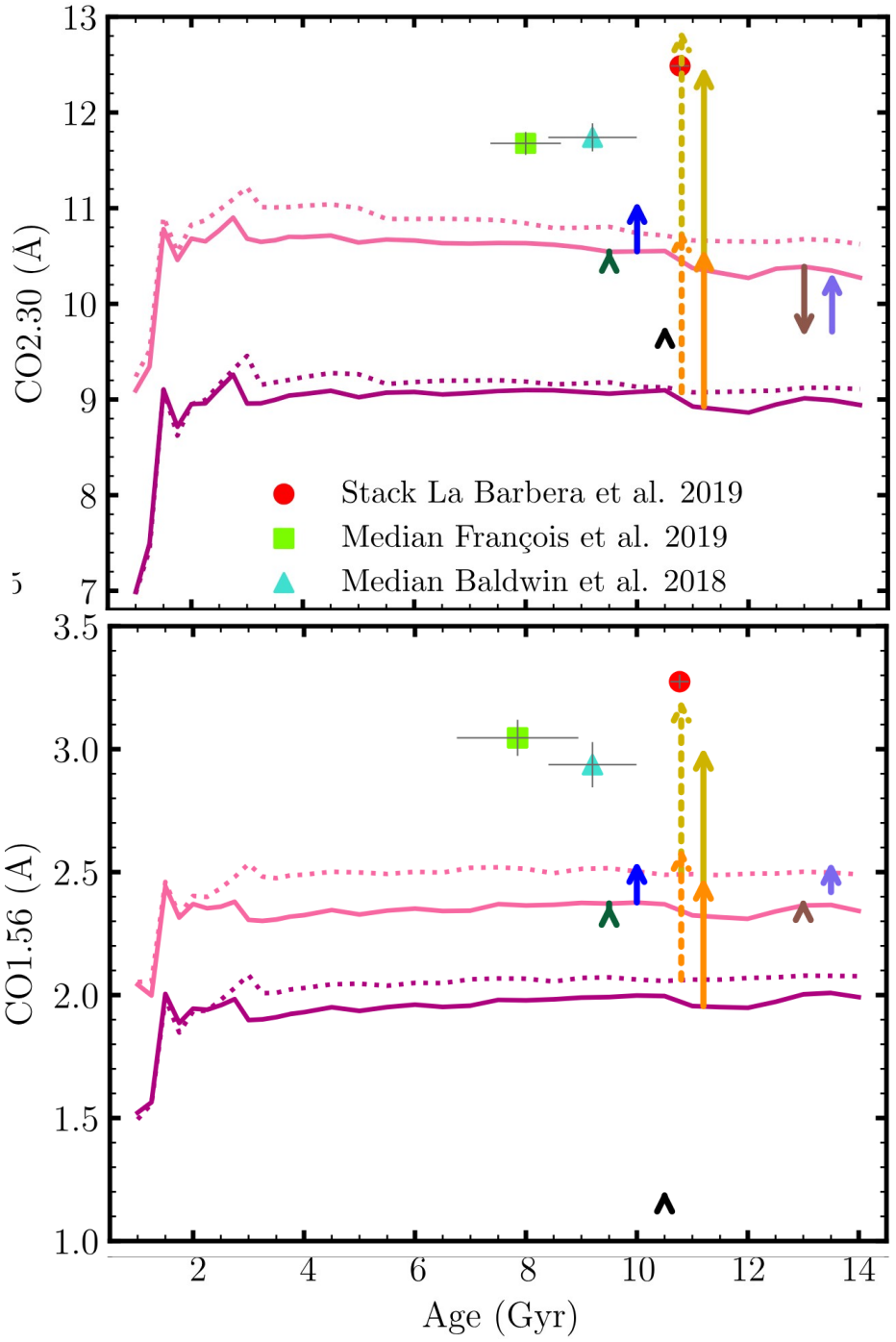
Le Cras+19



Young components:

Salvador-Rusiñol+20

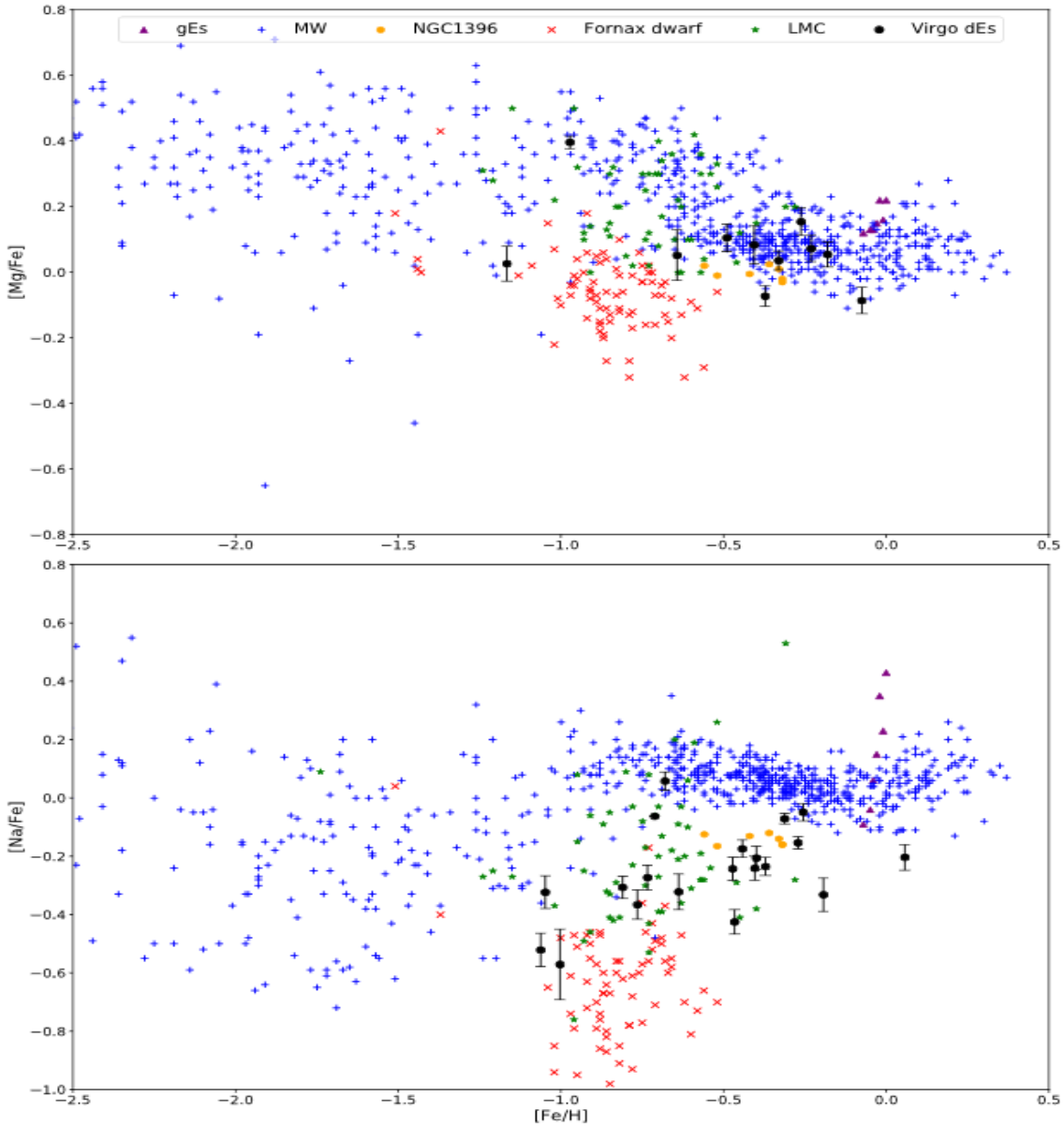
Opening the NIR window:



The CO challenge:

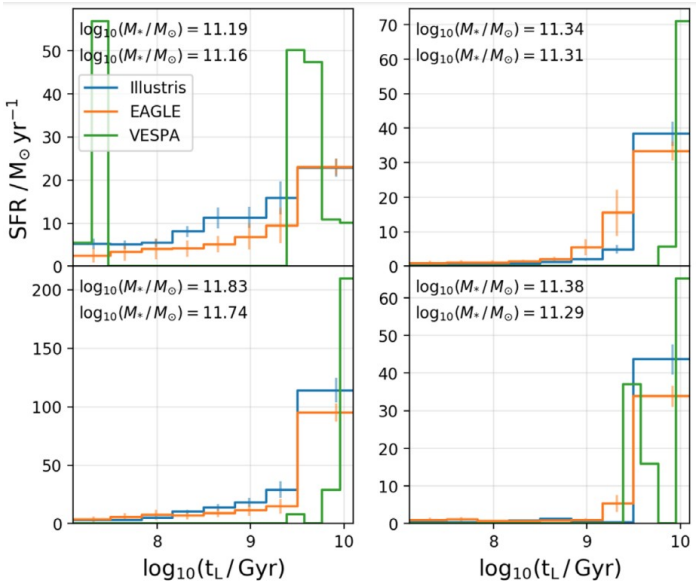
Eftekhari+22

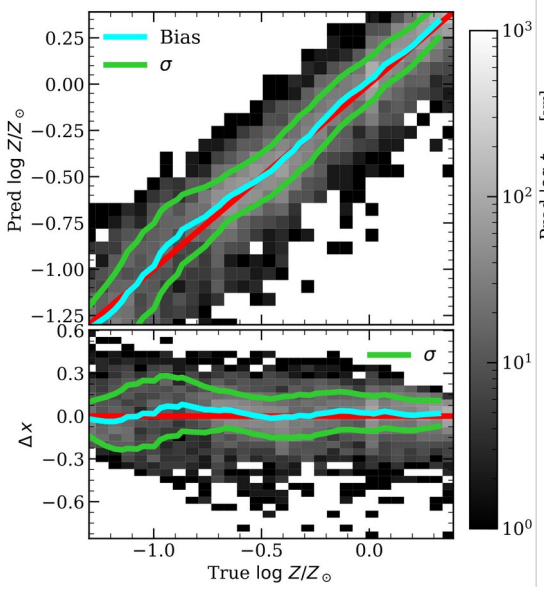
Dwarf Ellipticals:

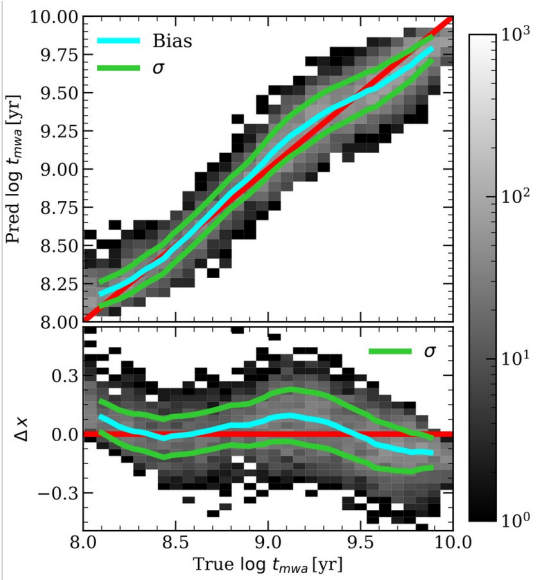


Sen+18

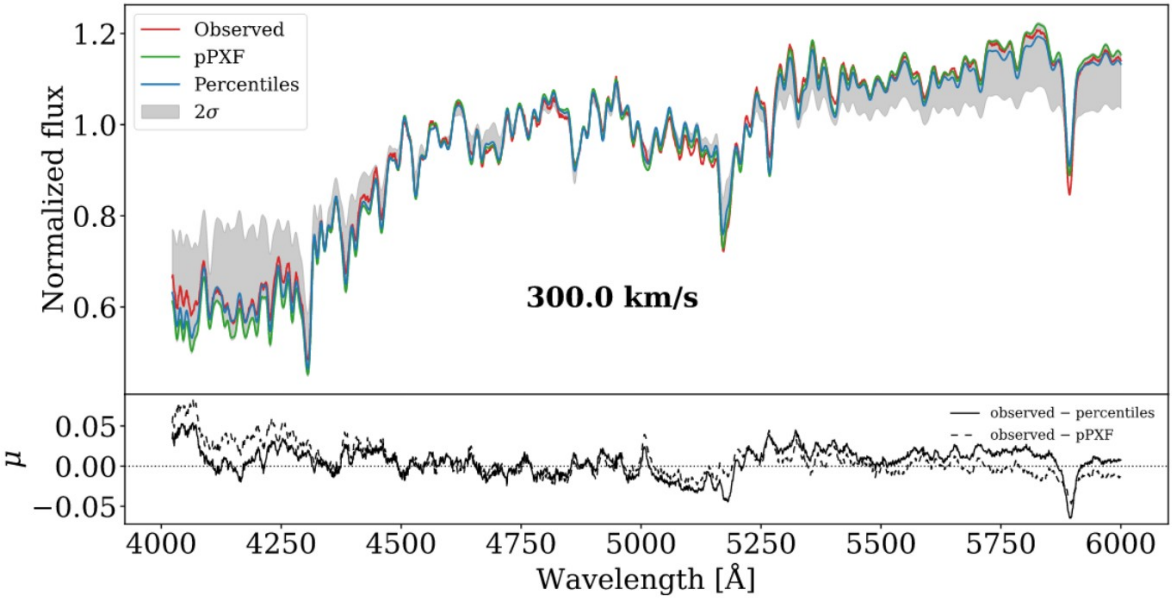
New fitting means







Photometry
(Lovell+19)



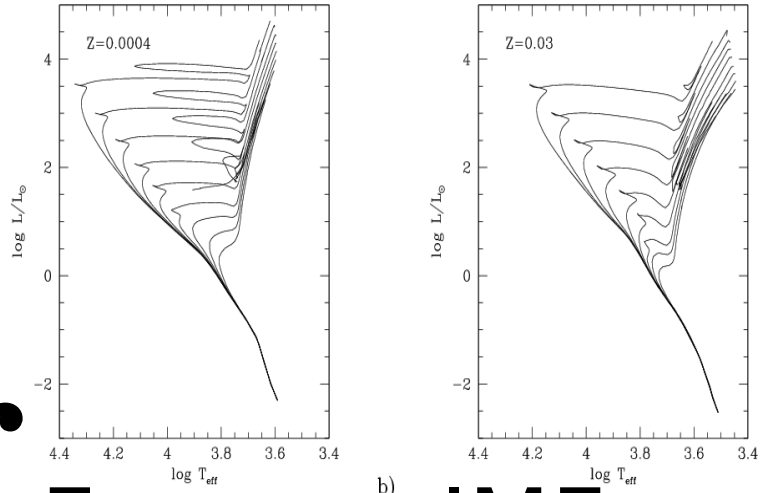
Line-indices
(Anghtopo+23)

Full spectra
(Iglesias-Navarro+24)

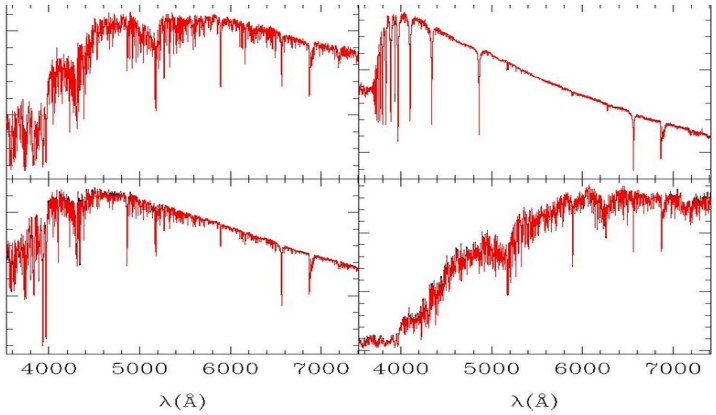
Stellar populations synthesis models

SSP

ISOCHRONES: BaSTI, Padova, MIST...

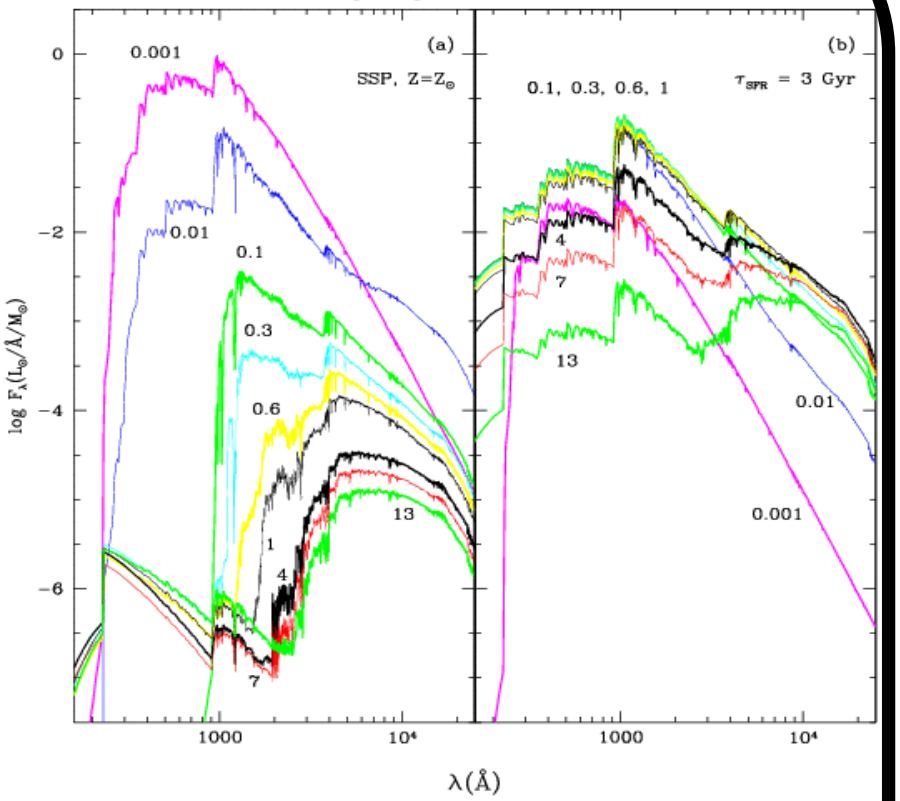


$$\int F_\lambda(m, T(t_0), g, Z)\, IMF(m)\, dm$$



STELLAR LIBRARIES:

- Theoretical (Kurucz, Phoenix,Coelho+..)
- Empirical (MILES, CaT, Indo-US, NGSL, IRTF, XSL, MaSTAR, ELODIE, STELIB,...)



- Photometric colours,M/L…
- Line-strength indices
- Spectra @ varying resolutions
- SBF

Model predictions:

- **Photometric properties** (fluxes, colours, M/L, Surface Brightnes fluctuations): Tinsley 80, Arimoto & Yoshii 86, Bruzual & Charlot 93, Buzzoni 94, Bressan+94, Worthey 94, Vazdekis+96, Kodama & Arimoto 97, Leitherer +98, Maraston 98,05

- **Line-strength indices** (Lick, Rose, CaII triplet,…): Peletier 89, Worthey 94, Vazdekis+96, Tantalo+98, Thomas+03, Schiavon+07

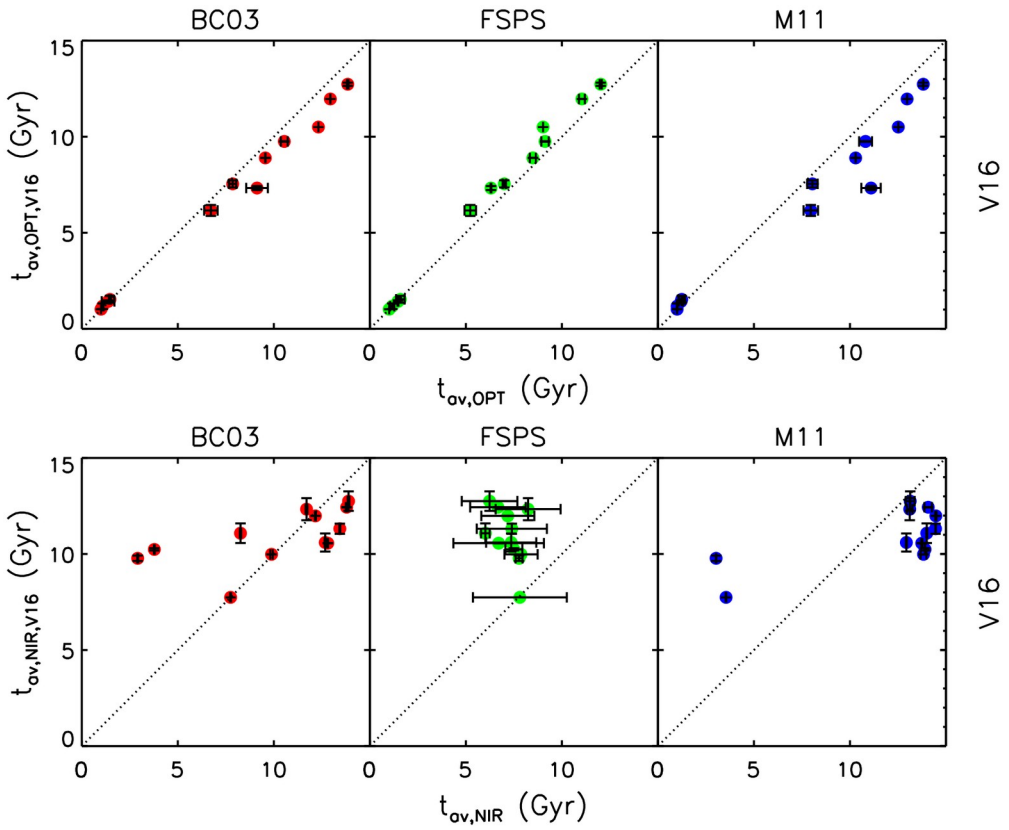
- **Low resolution spectra**: Bruzual & Charlot 93, Bressan+94, Kodama & Arimoto 97, Leitherer+98, Maraston 05, Conroy+09, Eldridge & Stanway 09

- **Spectra at moderately high resolution**: Vazdekis+99,03,10,12,16, Leitherer+99,10,14, Schiavon+00,02, Bruzual & Charlot 03, Le Borgne+04, Gonzalez-Delgado+05, Coelho+07, Buzzoni+09, Lee+09, Percival+09, Maraston+11,20, Conroy & van Dokkum 12,18, Meneses-Goytia+15, Röck+15, Stanway & Eldridge 18, Verro+22, Byrne+23, Park+24

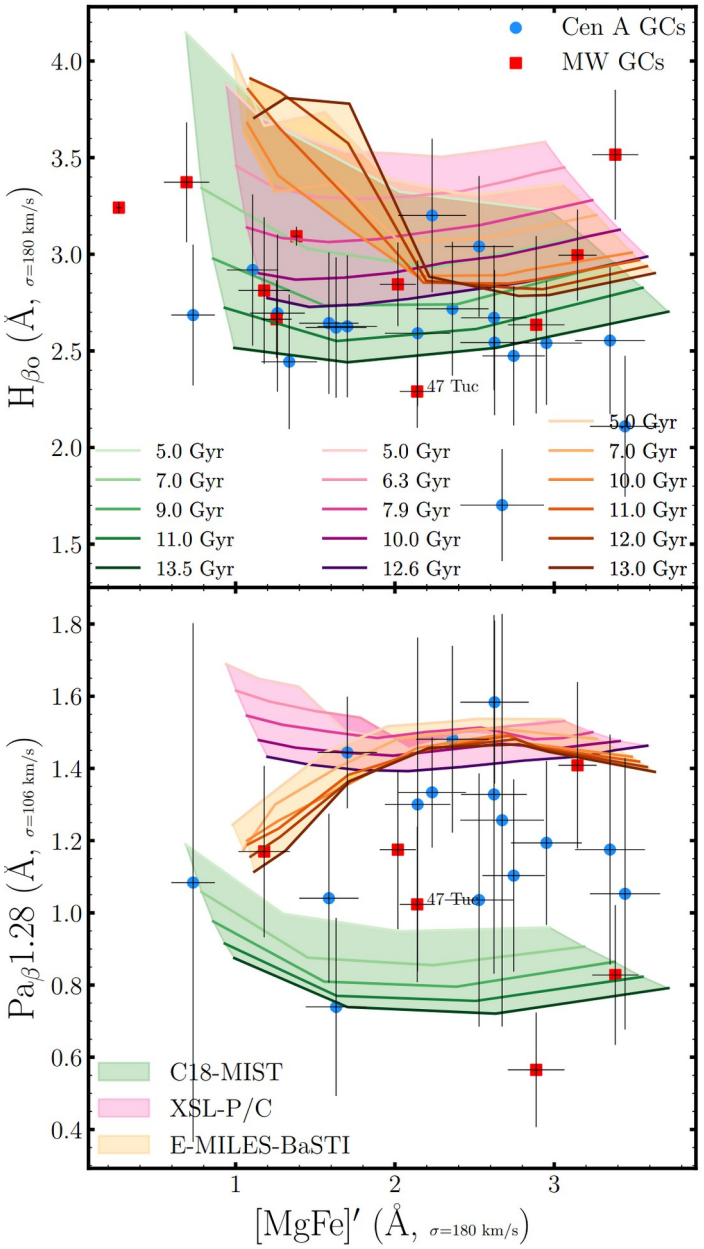
- **Surface Brightness Fluctuations spectra**: Mitzkus+18, Vazdekis+20

Model comparisons

Optical vs. IR predictions against galaxies & MW and Centaurus GCs



Baldwin+18



Eftekhari+24

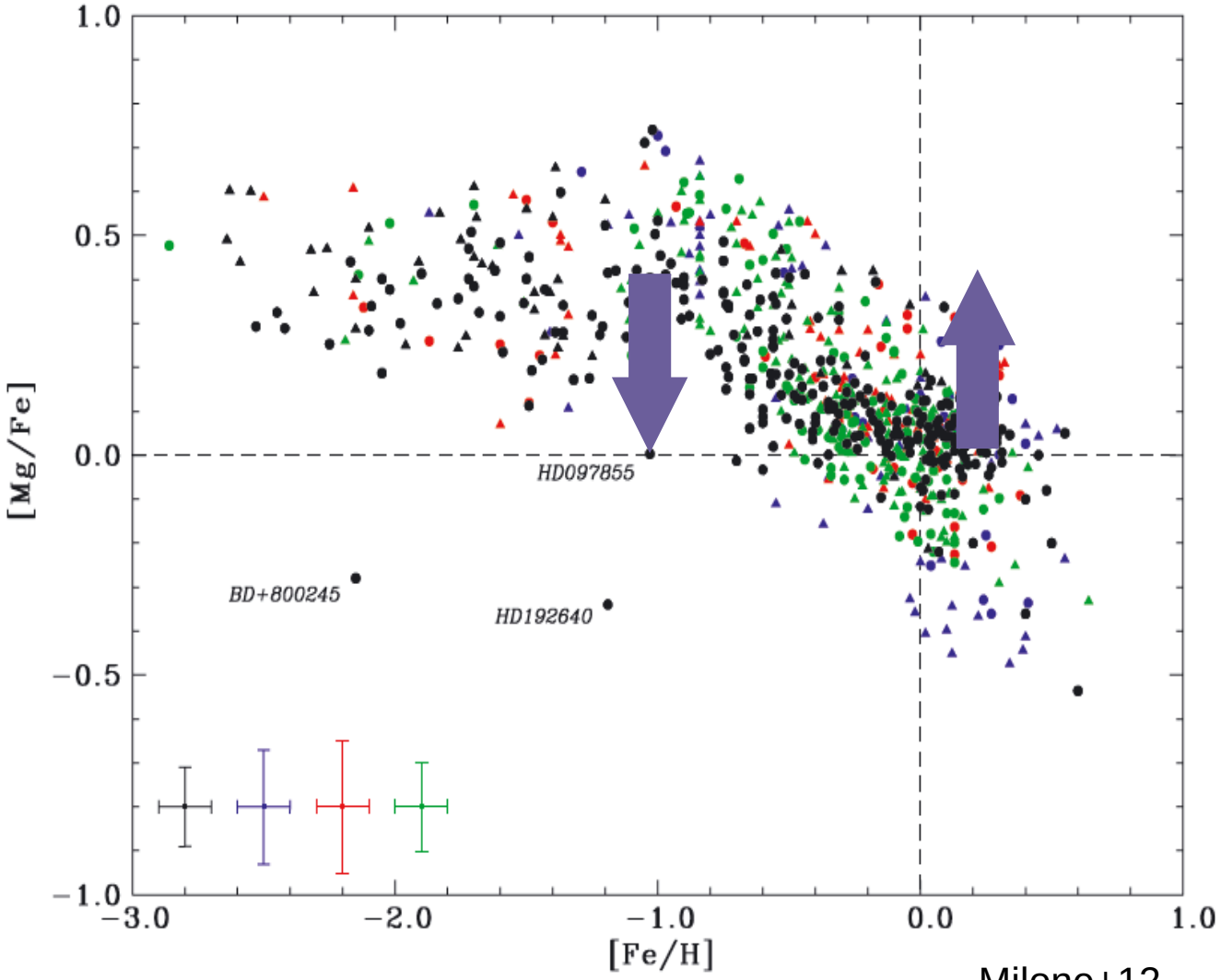
Models predicting SSP spectra with varying abundance ratios:

- **Base models (empirical stars following the MW abundance pattern):** Vazdekis 99,03,10,12,16, Schiavon+02, Bruzual & Charlot 03, Le Borgne+04, Maraston & Strömback 11, Maraston+20

- **Based on theoretical star spectra**: Coelho+07, Lee+09, Percival+09, Byrne+23, Park+24

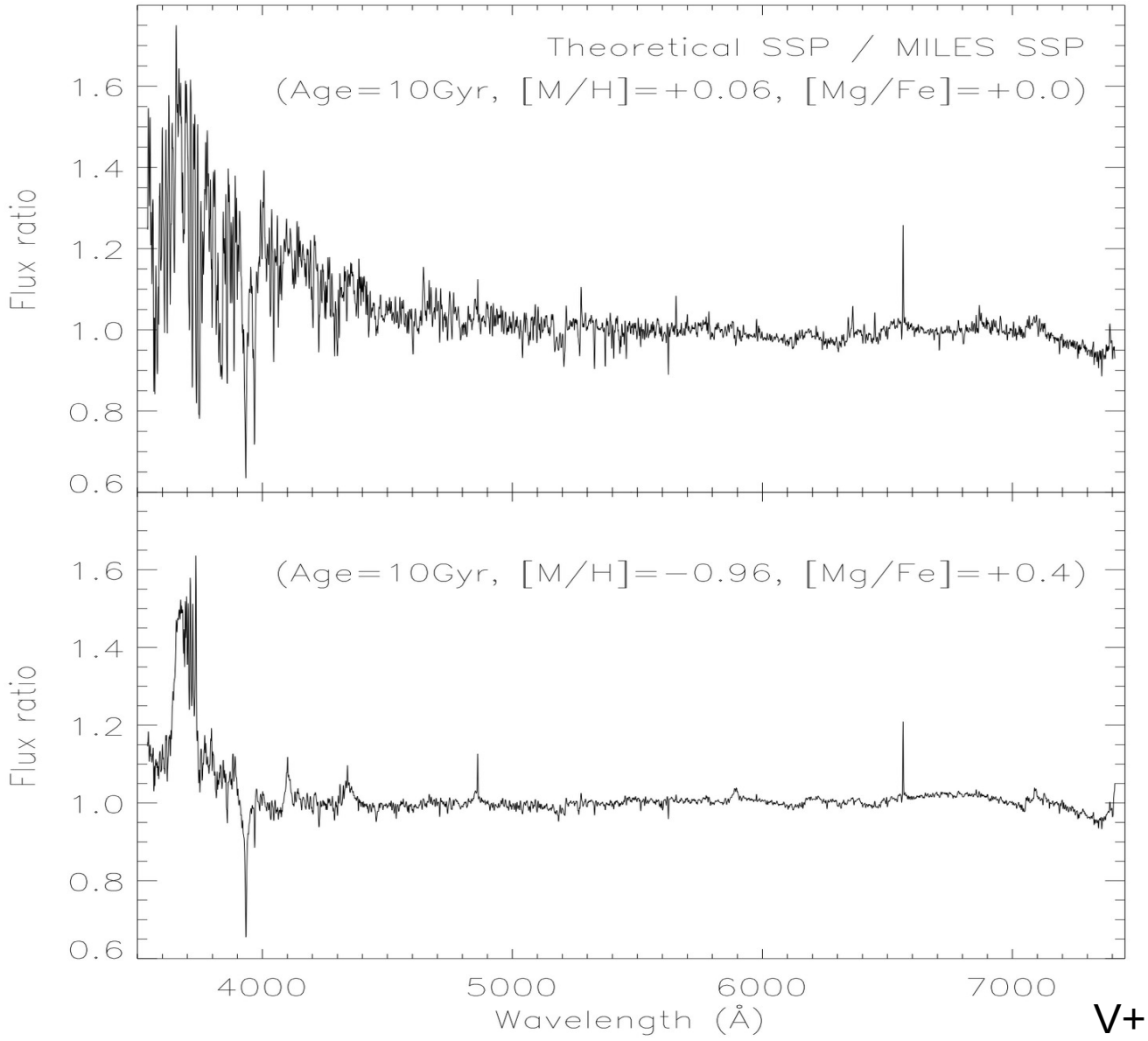
- **Based on empirical stars but corrected with theoretical differential spectral corrections:** Cervantes+07, Walker+09, Conroy & van Dokkum 12,18, Vazdekis+15, La Barbera+16, Knowles+23

Models built with Empirical vs Theoretical stars:



Milone+12

Models built with Empirical vs Theoretical stars:



V+15

Varying abundance ratios

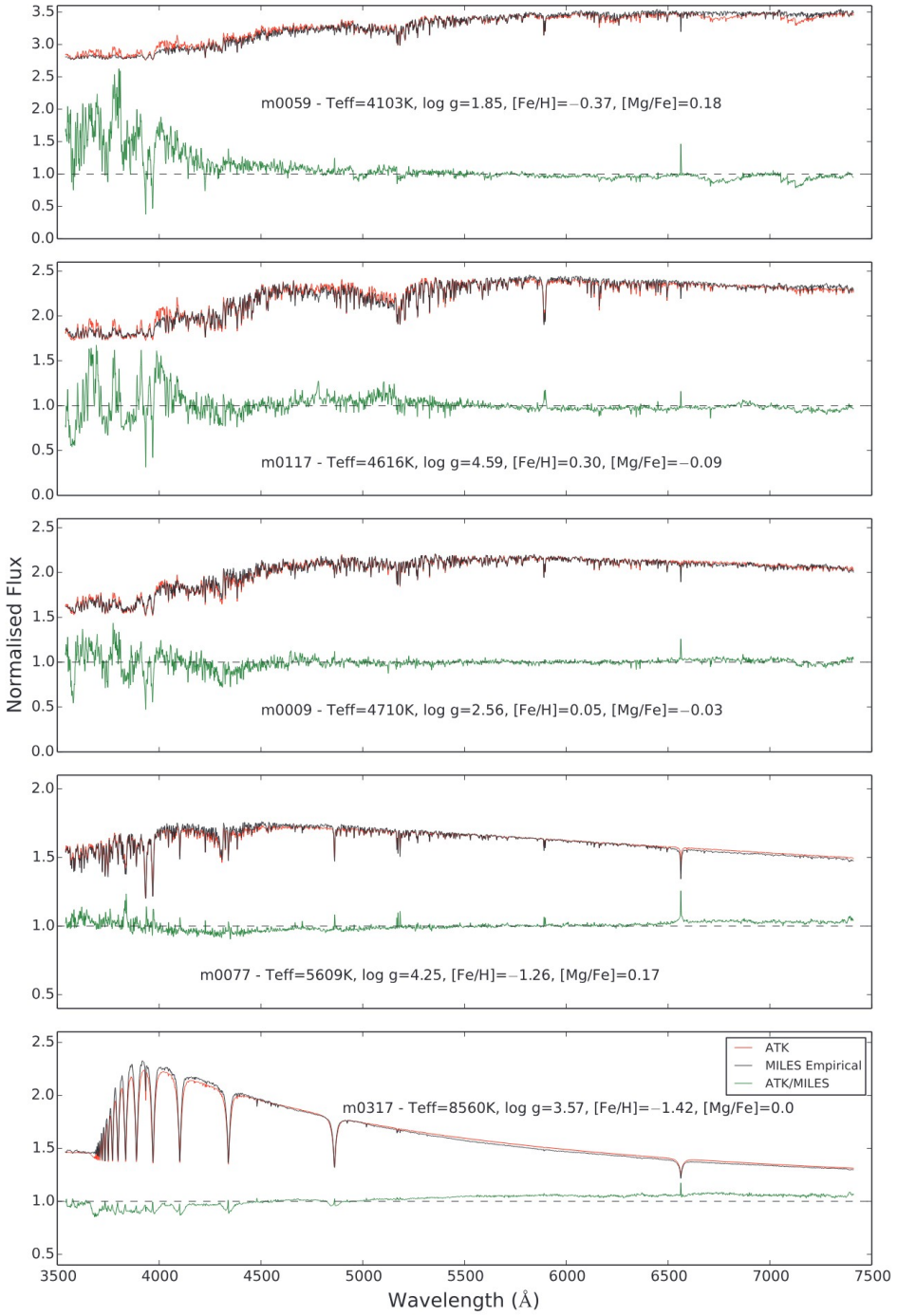
sMILES stellar library & SSPs

A. T. Knowles, A.E. Sansom, C. Allende Prieto

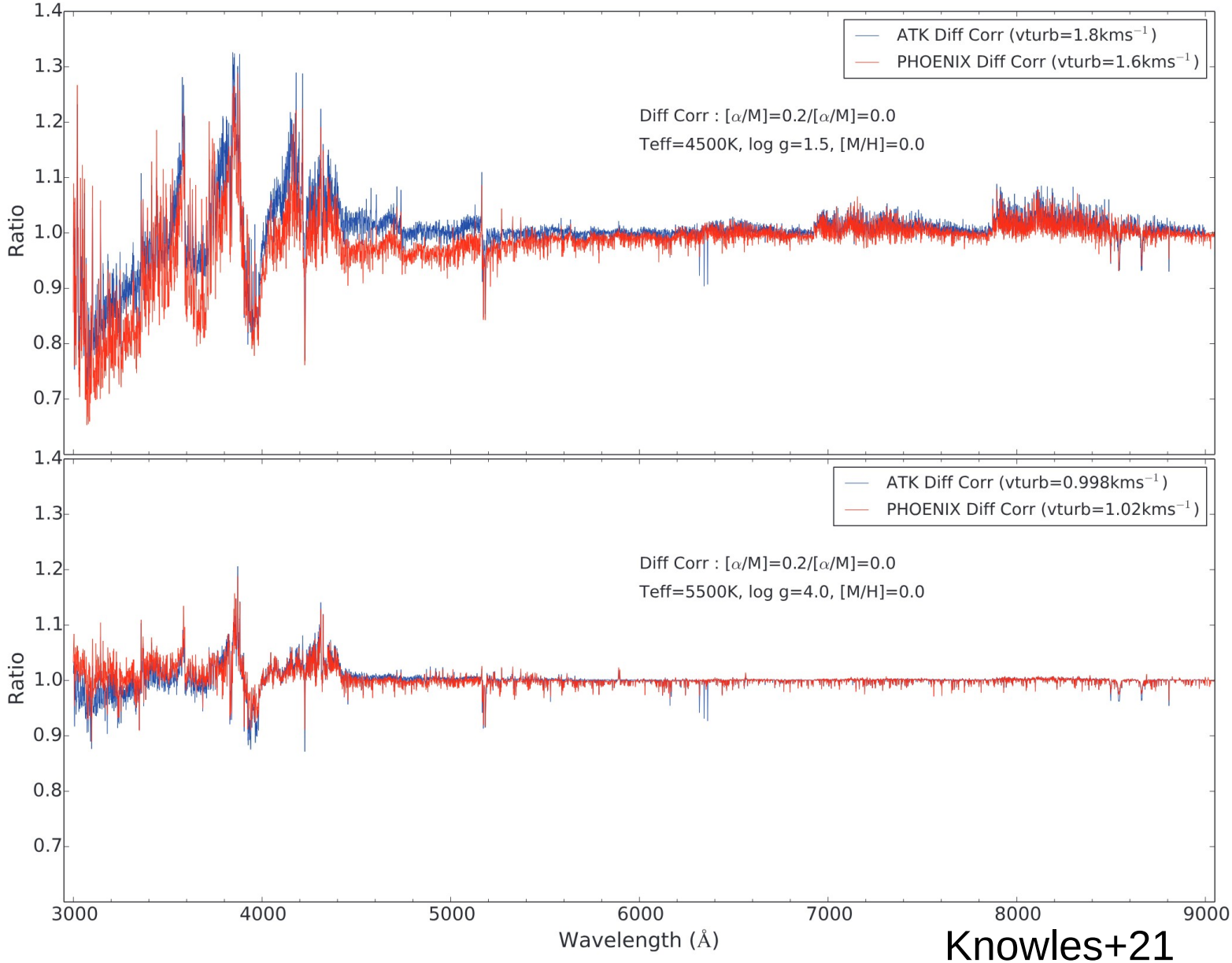
sMILES: a library of semi-empirical MILES stellar spectra

- Theoretical spectral computation:
  - Atlas9 model atmospheres
  - Radiative transfer: ASSET (1D,LTE)
  - Opacity Distribution Functions (Meszáros+12)
  - Solar abundance: Asplund+05
  - Line-lists (Allende+18)
  - Molecules: H2, CH, C2, CN, CO, NH, OH, MgH, SiH, SiO, TiO
  - vturb (Teff,logg) (Knowles+21)

Knowles+21

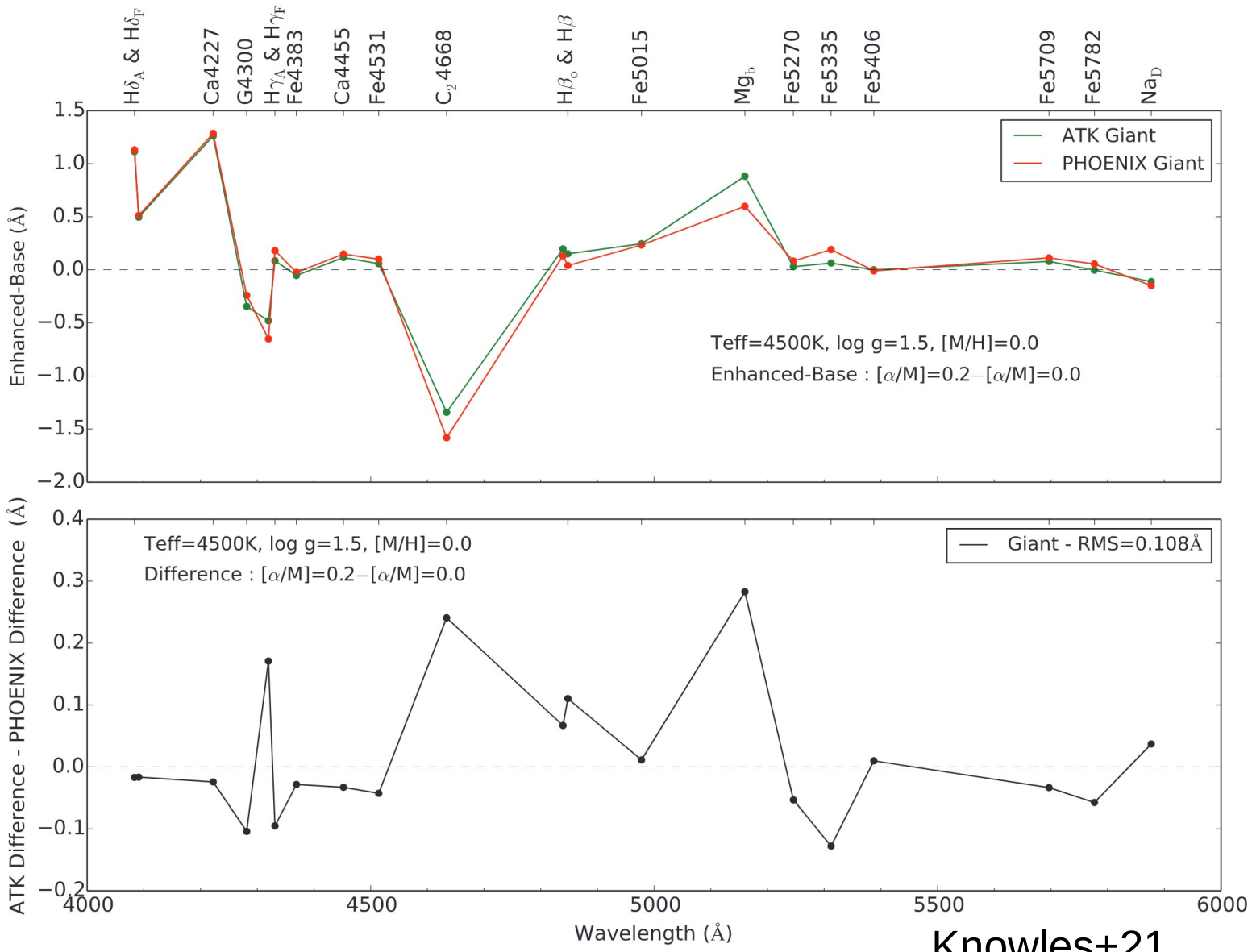


Differential corrections:



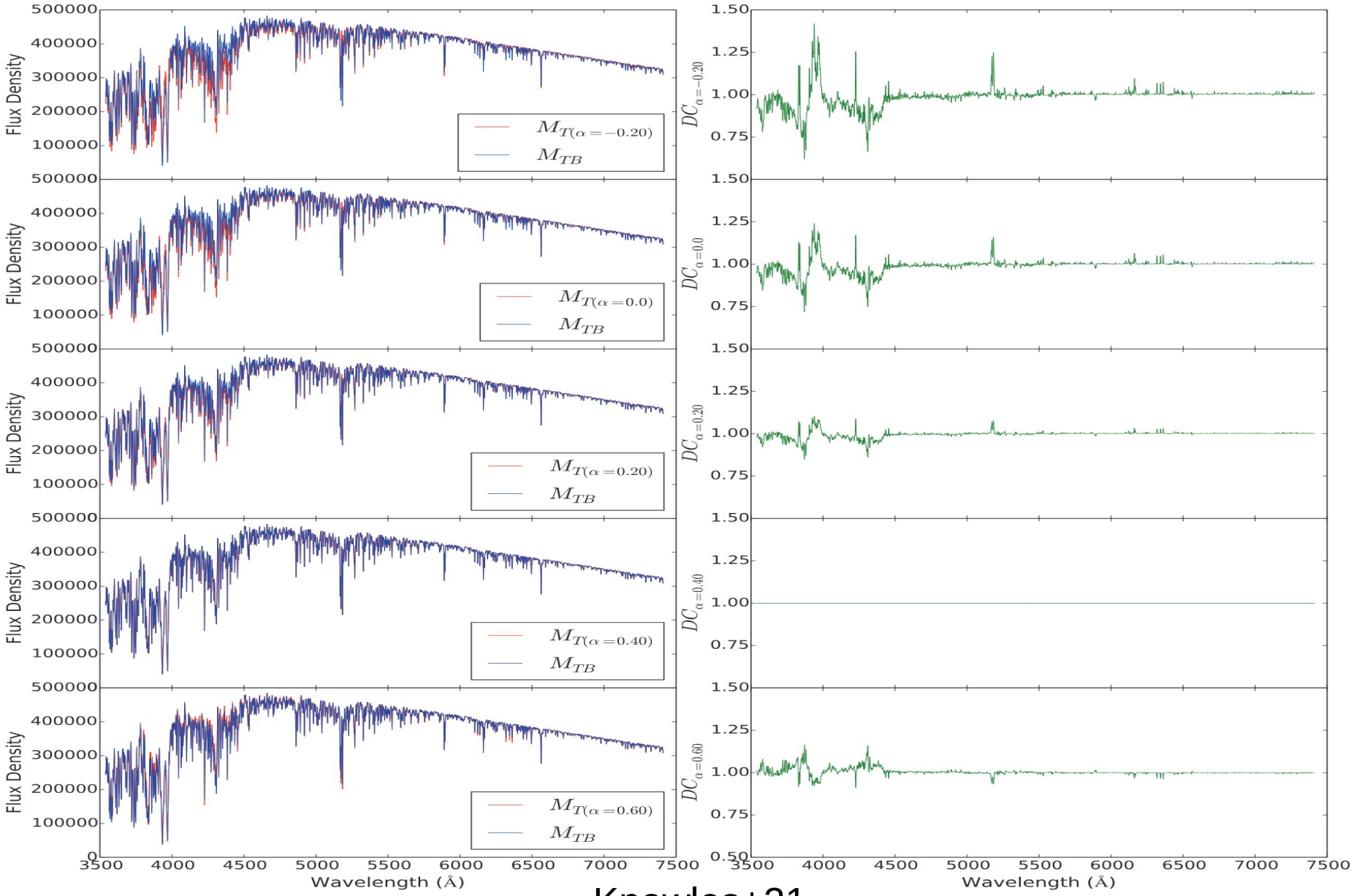
Knowles+21

Impact of differential corrections on indices:



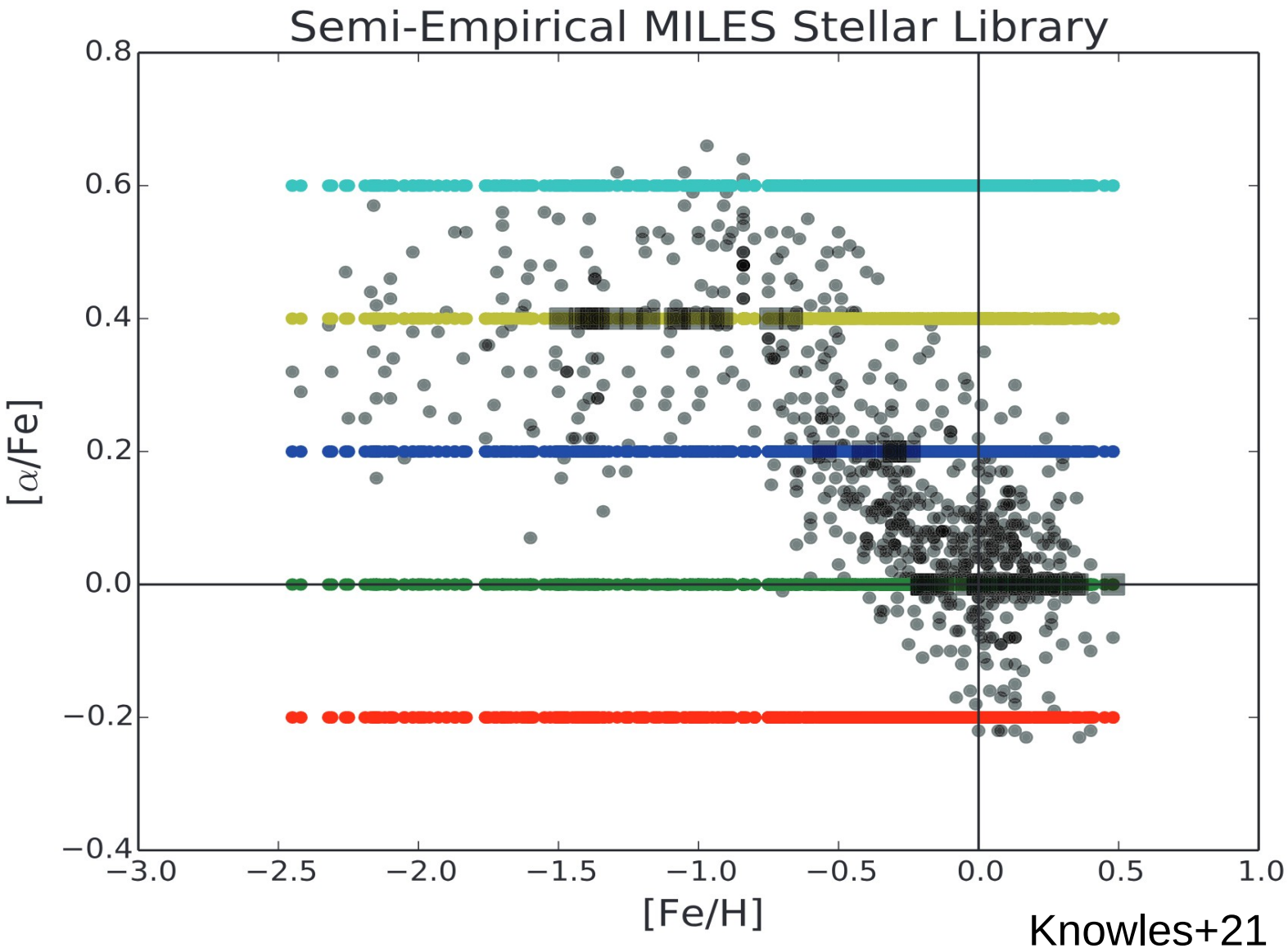
Knowles+21

Semi-empirical SMILES star spectra:



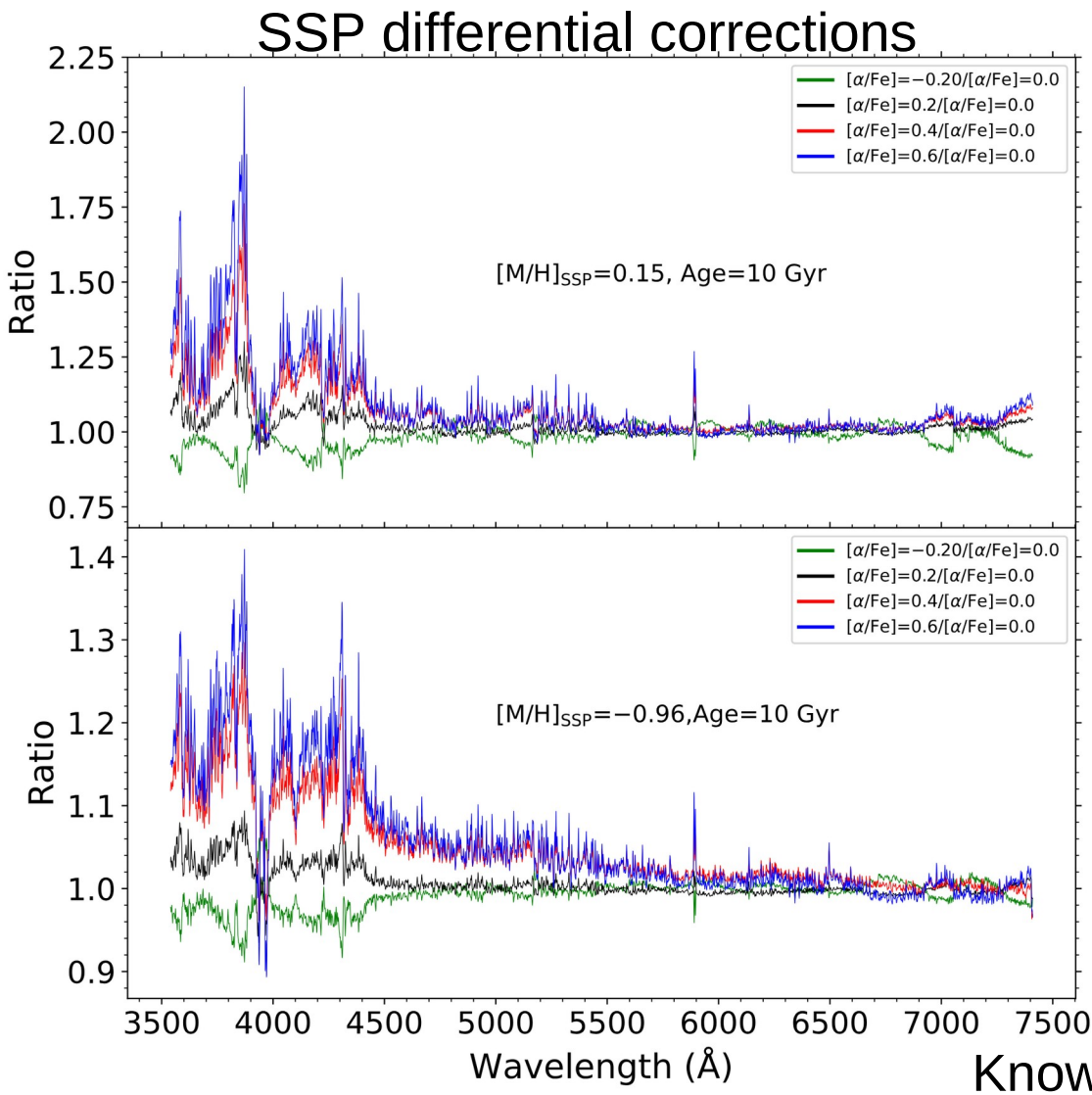
Knowles+21

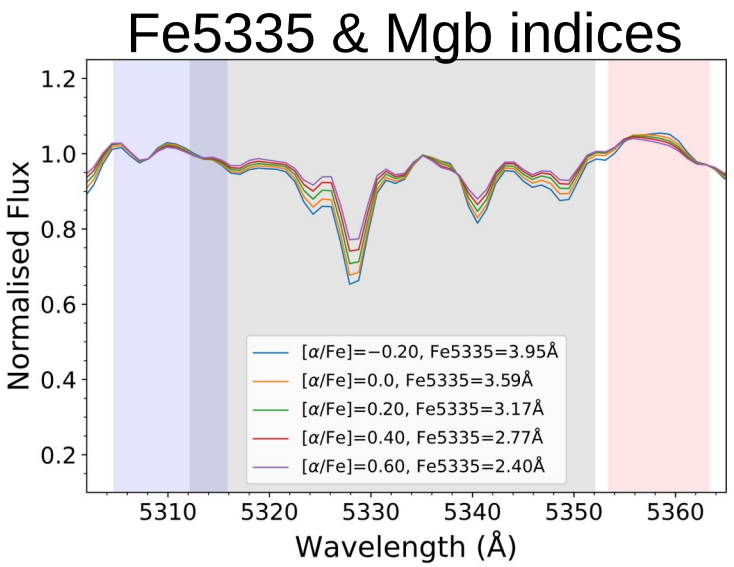
sMILES grid:

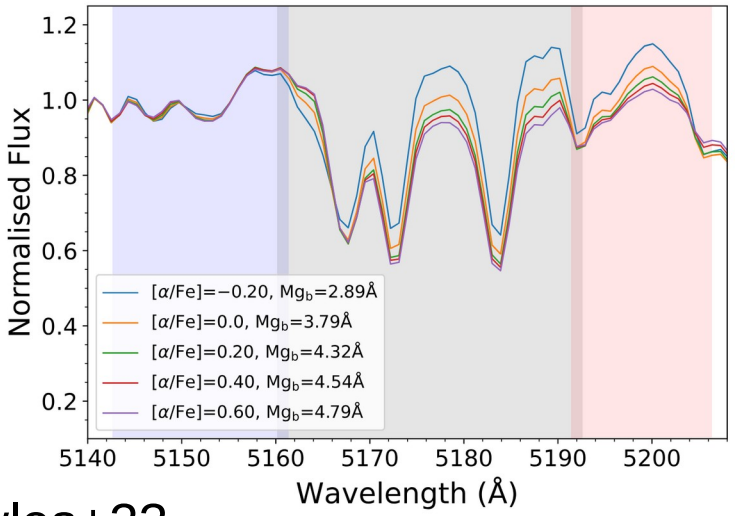


Knowles+21

sMILES SSPs

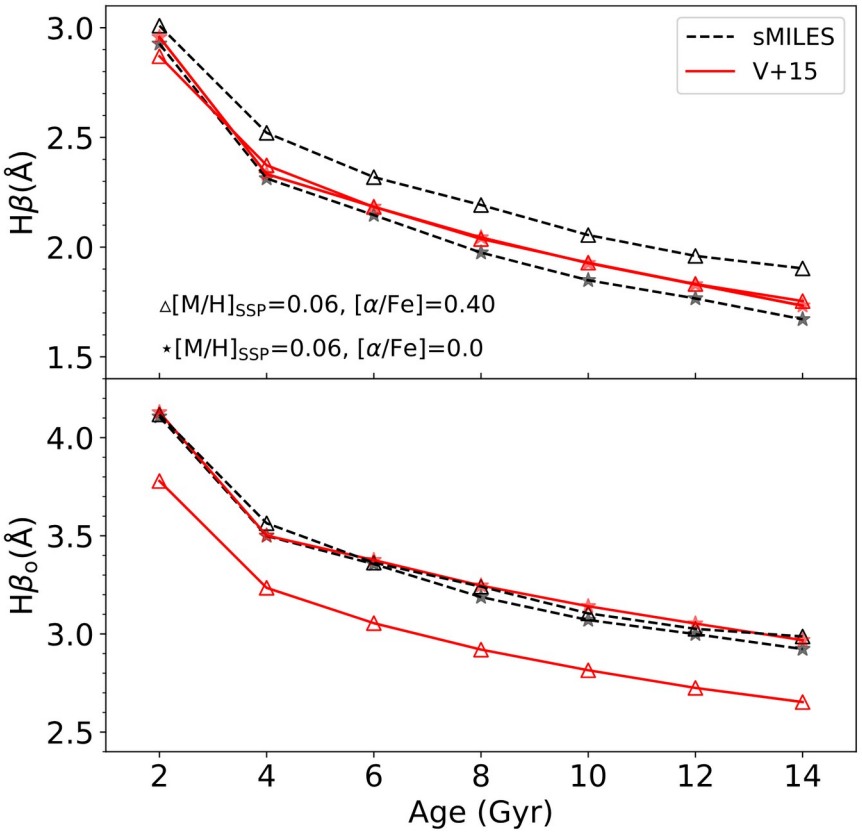


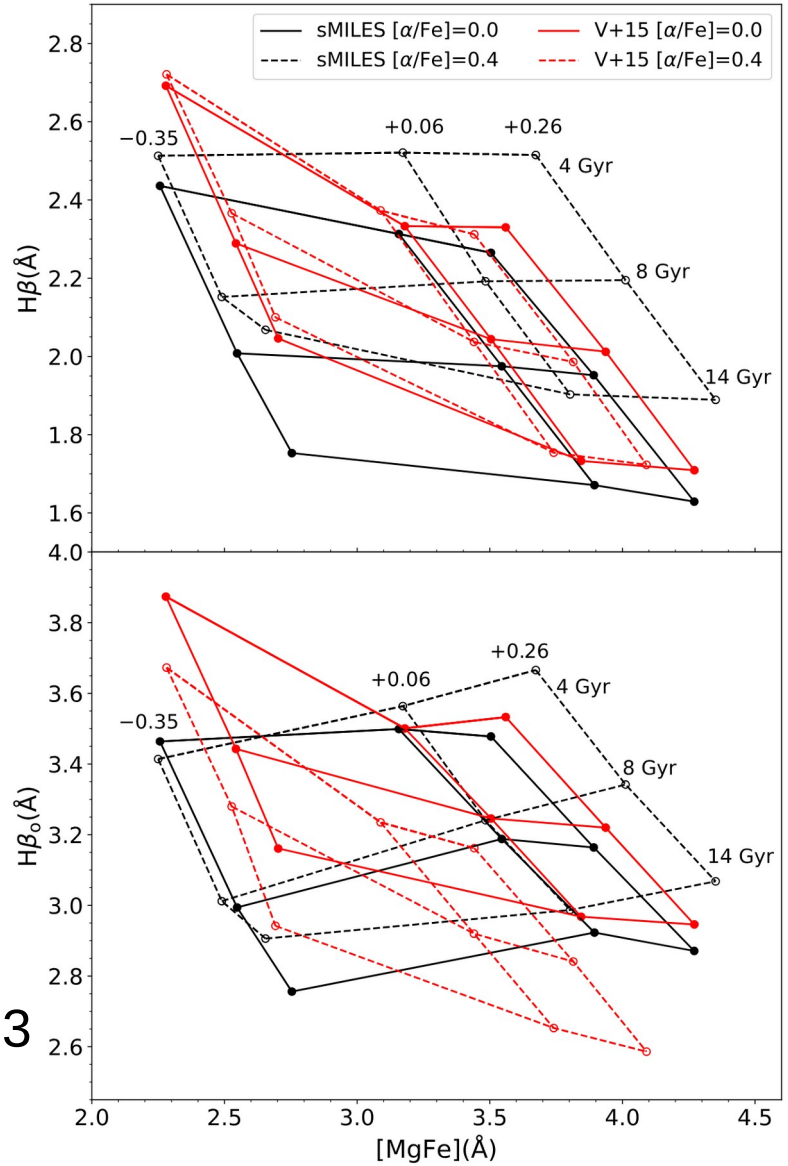




Knowles+23

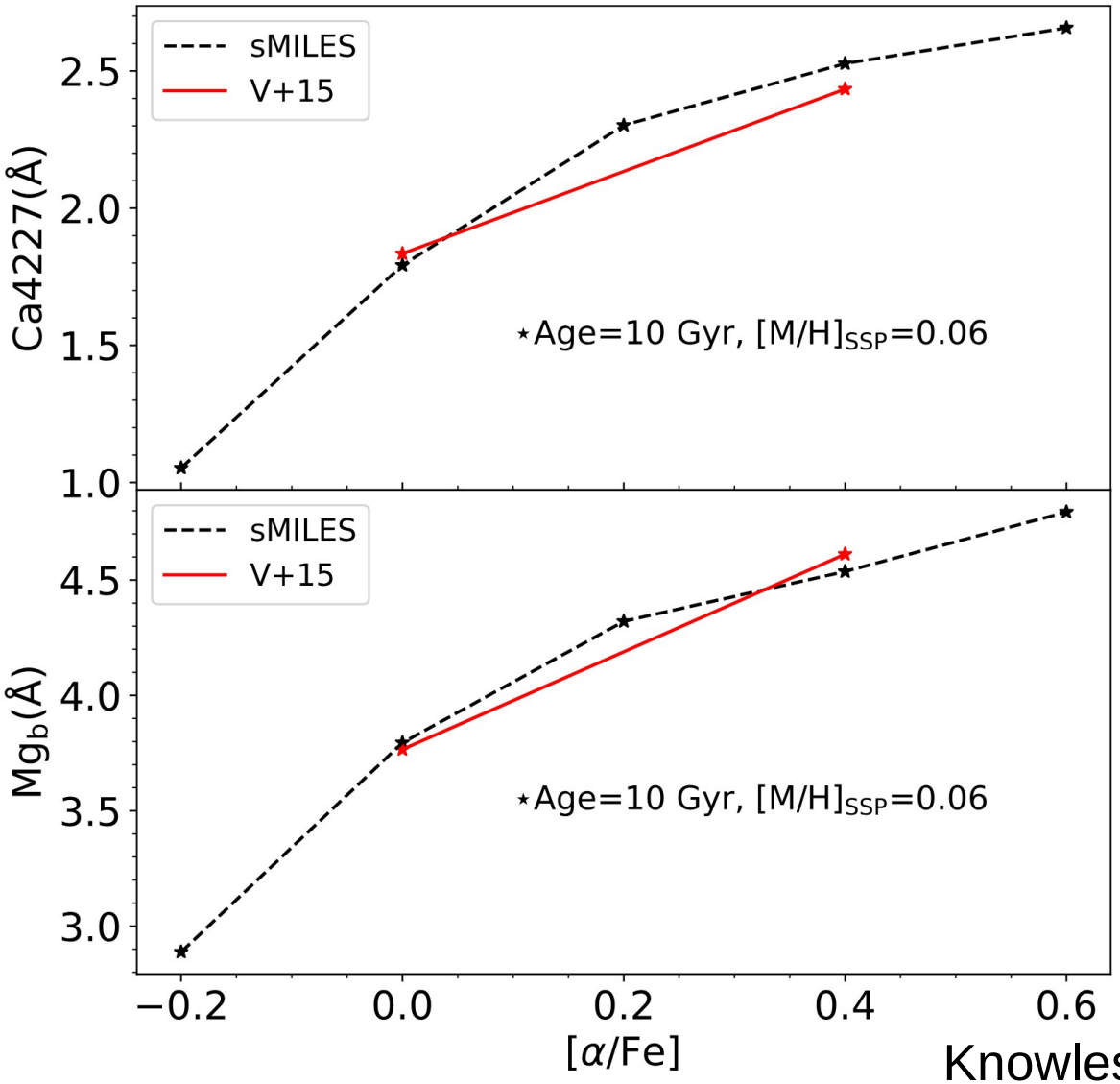
Impact of varying differential corrections on key indices:





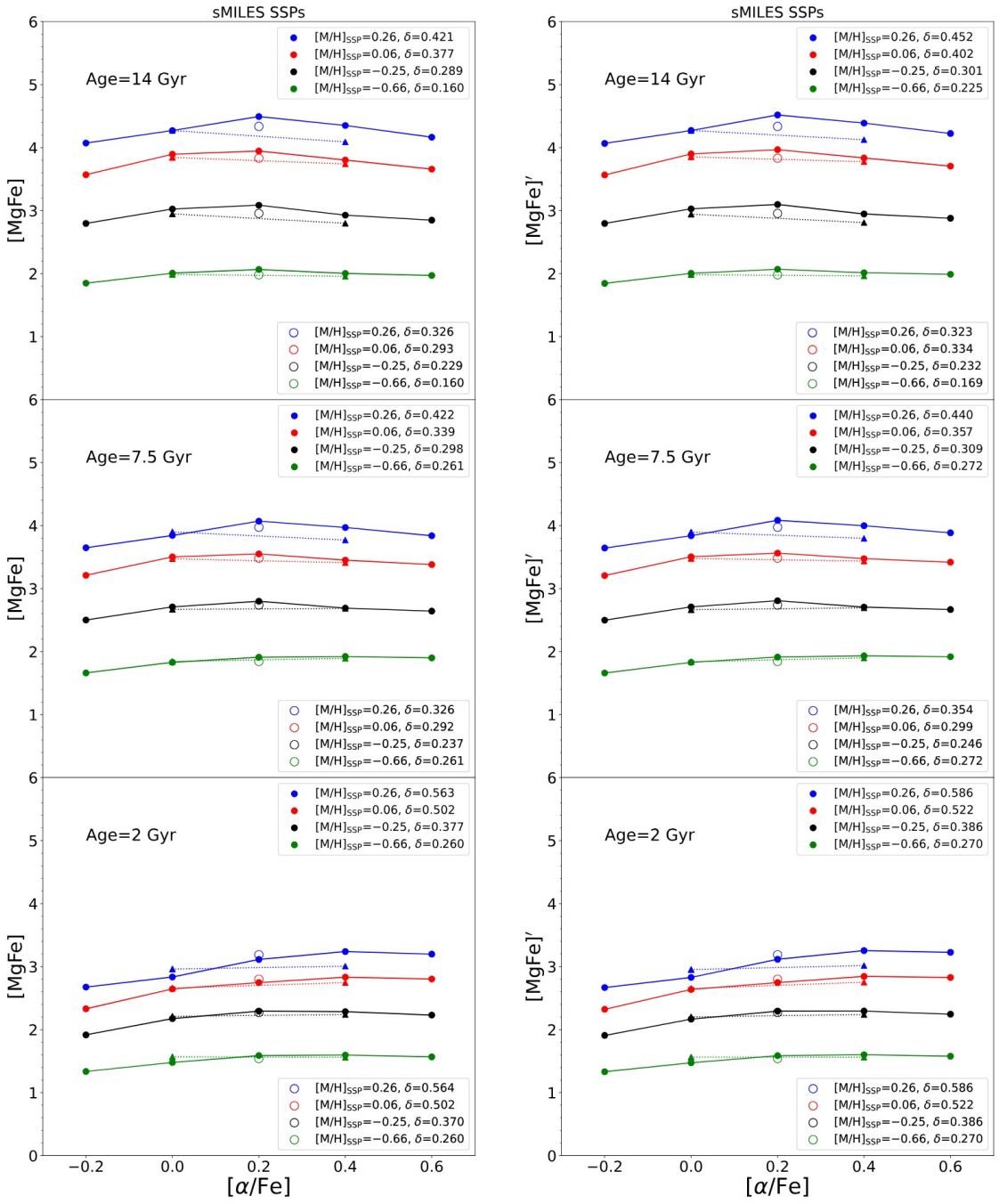
Knowles+23

Non-linear index responses:



Knowles+23

[α/Fe] insensitive indices:



Knowles+23

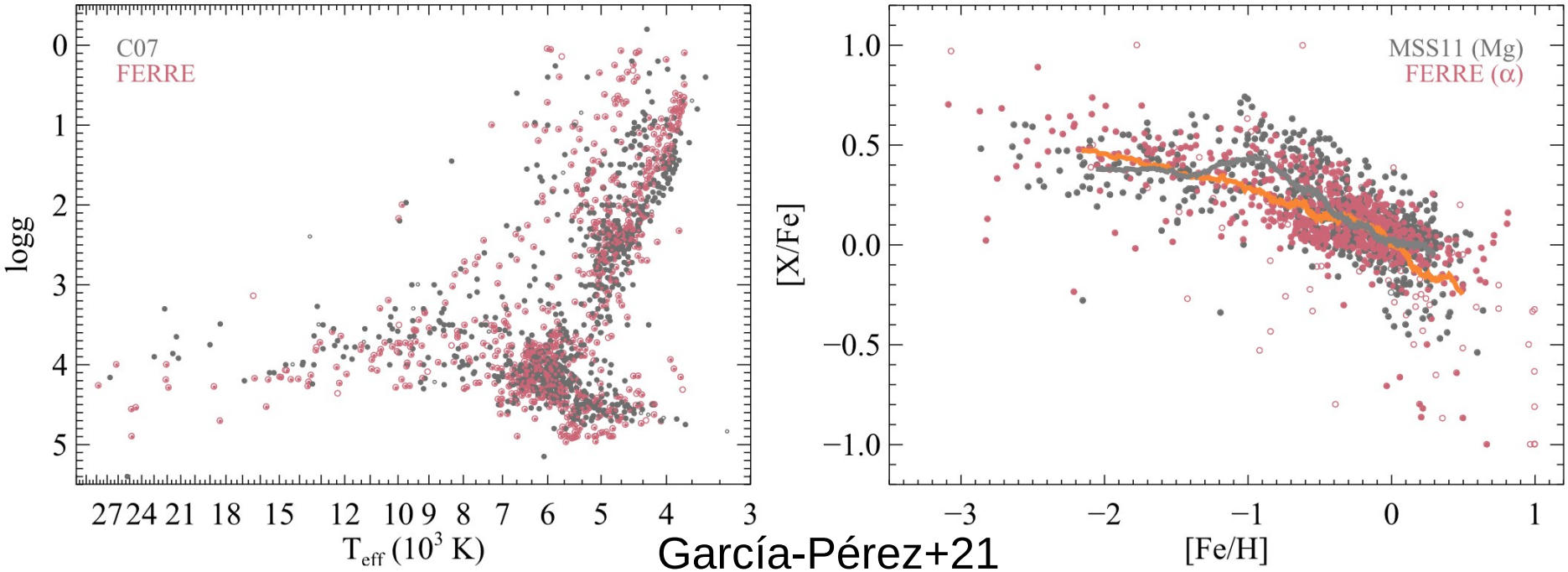
New abundance ratio determinations in library stars

MILES & XSL libraries

A.E. García-Pérez, C. P. Santos-Peral, P. Sánchez-Blázquez, Allende-Prieto, A. de C. Milone, A. E. Sansom, J. Gorgas, J. Falcón-Barroso, I. Martín-Navarro, R. Cacho
P.A. Palicio

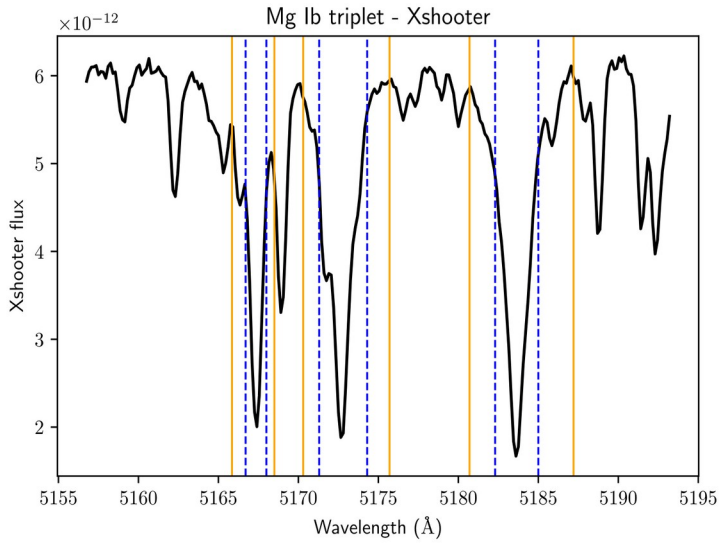
[α/Fe] determinations of extended MILES star library:

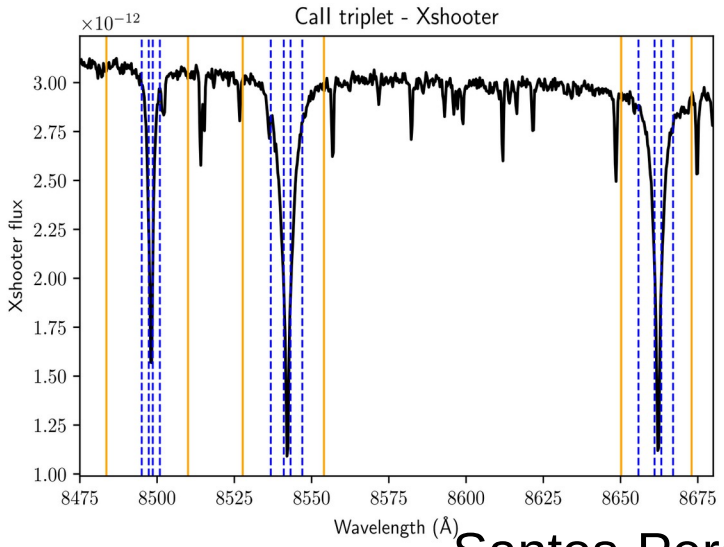
- ~200 new stars observed @ INT with similar set-up & S/N as original ones
- Teff,logg,[M/H] and [α/Fe], derived by fitting the spectra with FERRE + theoretical library (Allende-Prieto+18)



García-Pérez+21

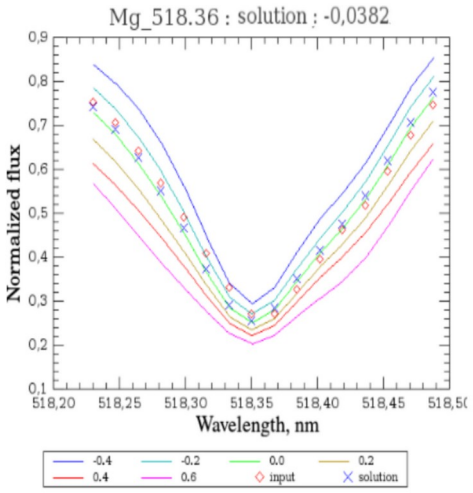
[Mg/Fe] & [Ca/Fe] determinations in XSL stars:

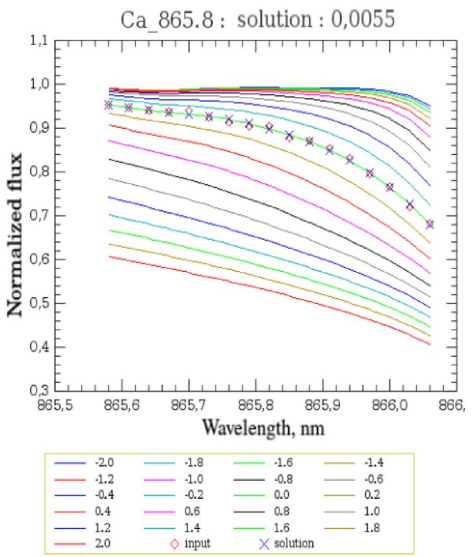




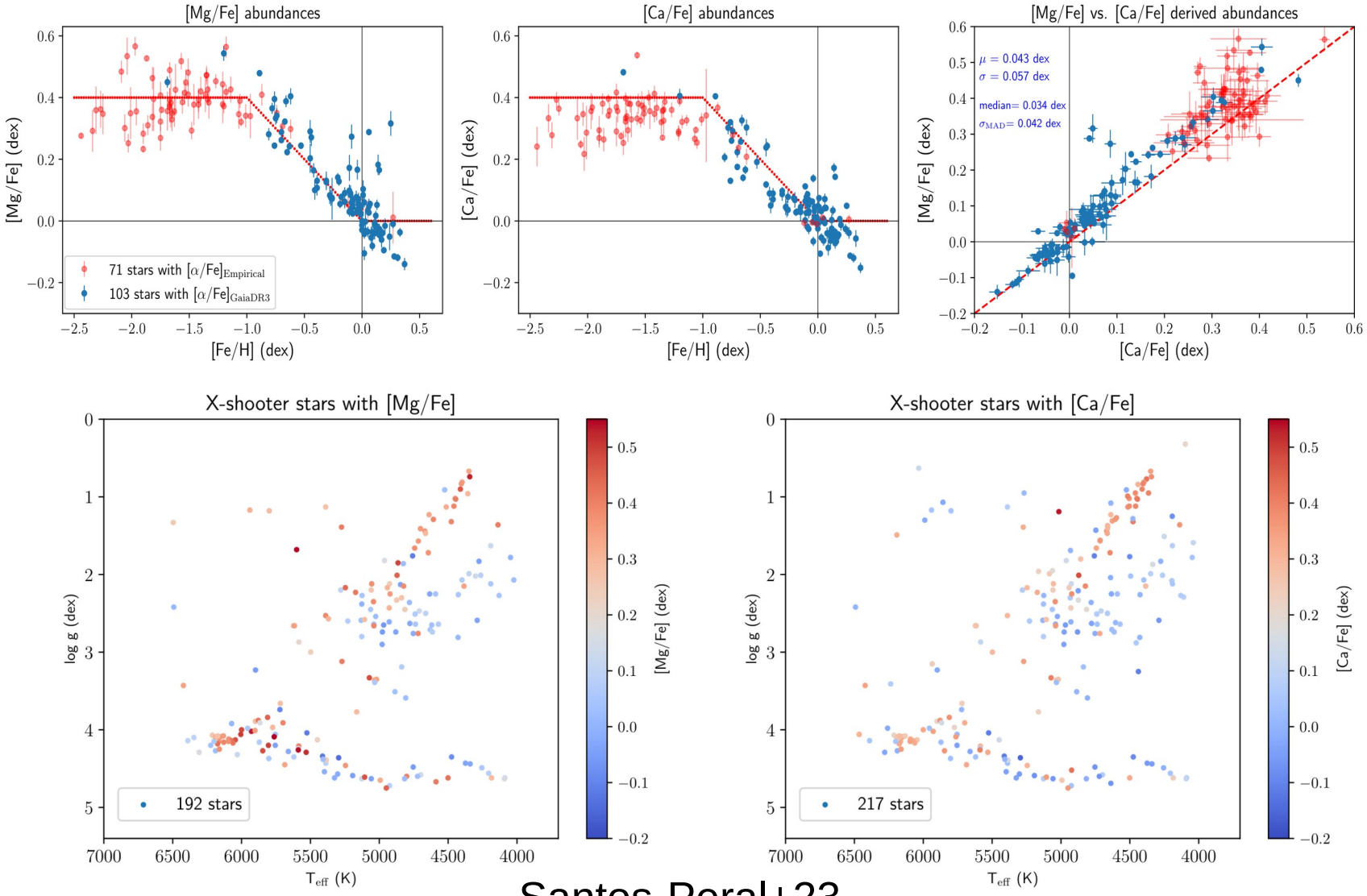
Santos-Peral+23

- Star parameters (Arentsen+19): validated with Gaia RVS & AMBRE
- Synthesis: TURBOSPECTRUM (Plez 12)
- Atmospheres: MARCS (1D, LTE)
- Gauguin (Bijaoui+12; Recio-Blanco+16):
  - Mg Ib lines
  - Ca II Triplet lines
    ([α/Fe] from Gaia DR3 (when available)





[Mg/Fe] & [Ca/Fe] determinations in XSL stars:



Santos-Peral+23

Increasing the spectral resolution

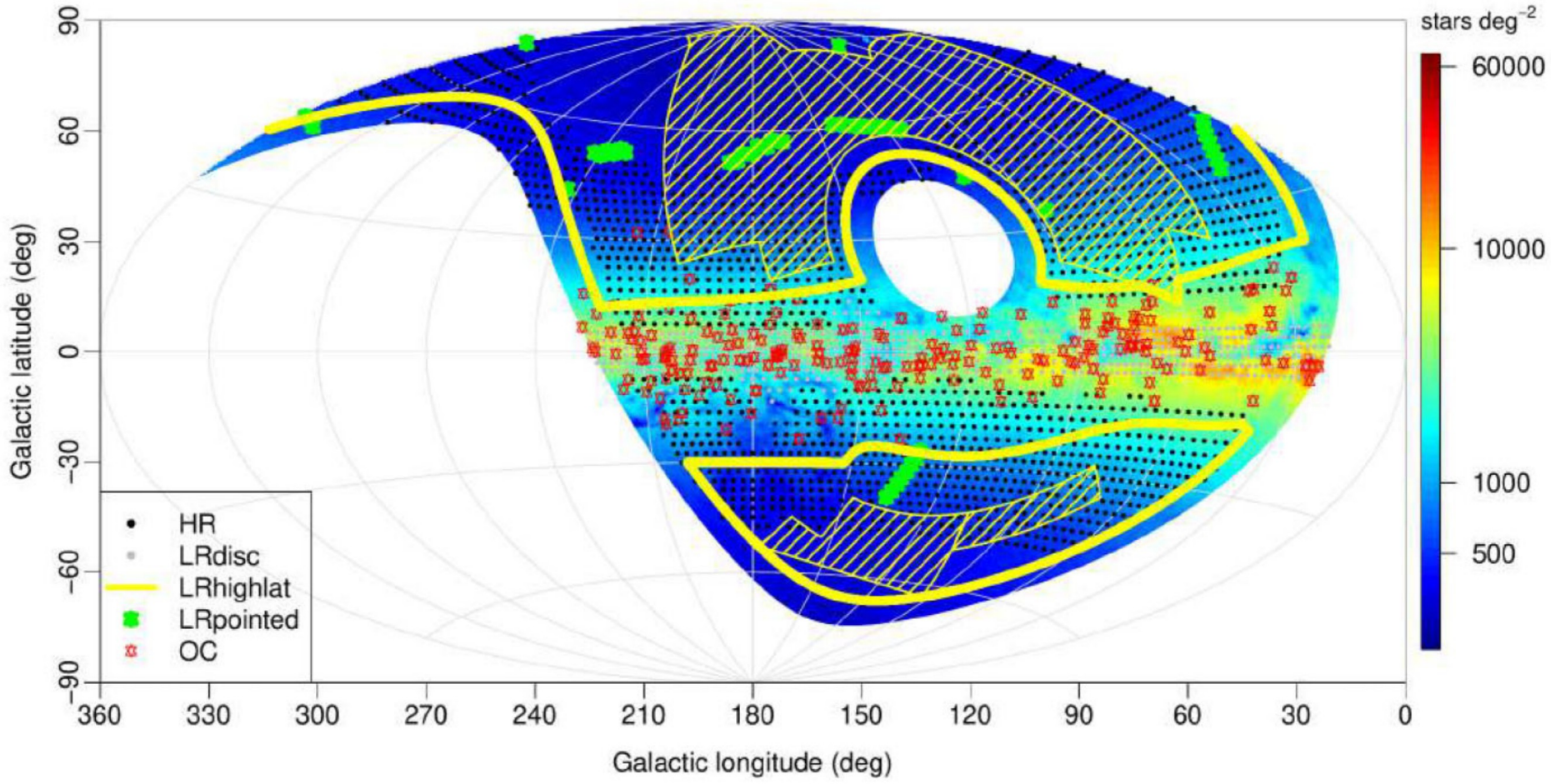
WEAVELIB: WEAVE Stellar Library Project

A. Aguerri (WC), G. Battaglia (GA), del Burgo, C. (WC), J. Falcón-Barroso (WA), A. Gallazzi (StePS), R. Peletier (WC), R. Raddi (WD), S. Simón-Díaz (SCIP), R. Sordo (GA-OC)

Increasing the resolution: WEAVELIB

- Library assembly:
  - Star-targeted surveys: GA, SCIP, Twilight stars, …
  - Galaxy-targeted surveys: StePS, WEAVE Apertif…
- WEAVELIB star spectra:
  - Resolution: 5000
  - Spectral coverage: 3660-6060Å + 5790-9590Å
    (gaps: 5491-5539Å, 7590-7669Å)
  - Homogeneous stellar atmospheric parameters
  - Stellar parameter coverage contributed by varying surveys footprints
  - Flux-calibrated
- Time schedule:
  - Linked to WEAVE surveys

Surveys footprints



Jin+24

GA survey

- High-Latitude LR survey (LR-highlat):
  - 1.5 mill sources covering 8500 deg² Galactic halo: 10-100kpc
  - 15 < r < 20-21 (Gaia RVS)
  - 250 deg² r < 21.5 (4h exp.)
  - Gaia Enceladus, Gaia Sausage, …
  - Star types:
    - MSTO
    - Red Giants (Gaia astrometry).
    - EMPs
    - BHB
    - RRLyrae
- LR-disc (Disc-Dynamics LR survey):
  - 10^6 stars
    (ID sub-survey: ~760.000 * ; MD sub-survey: ~60.000; OD sub-survey: ~260.000)
  - 15 < r < 19
  - Inner disc, bar, spiral arms, outer disc
  - Red clump giants
- Fraction in GA Open Clusters sub survey footprint
- Bad weather → HR targets in LR

GA survey WEAVELIB candidates

Mostly driven by obtained S/N > 50: ~15% MSTO + ~20% Giants

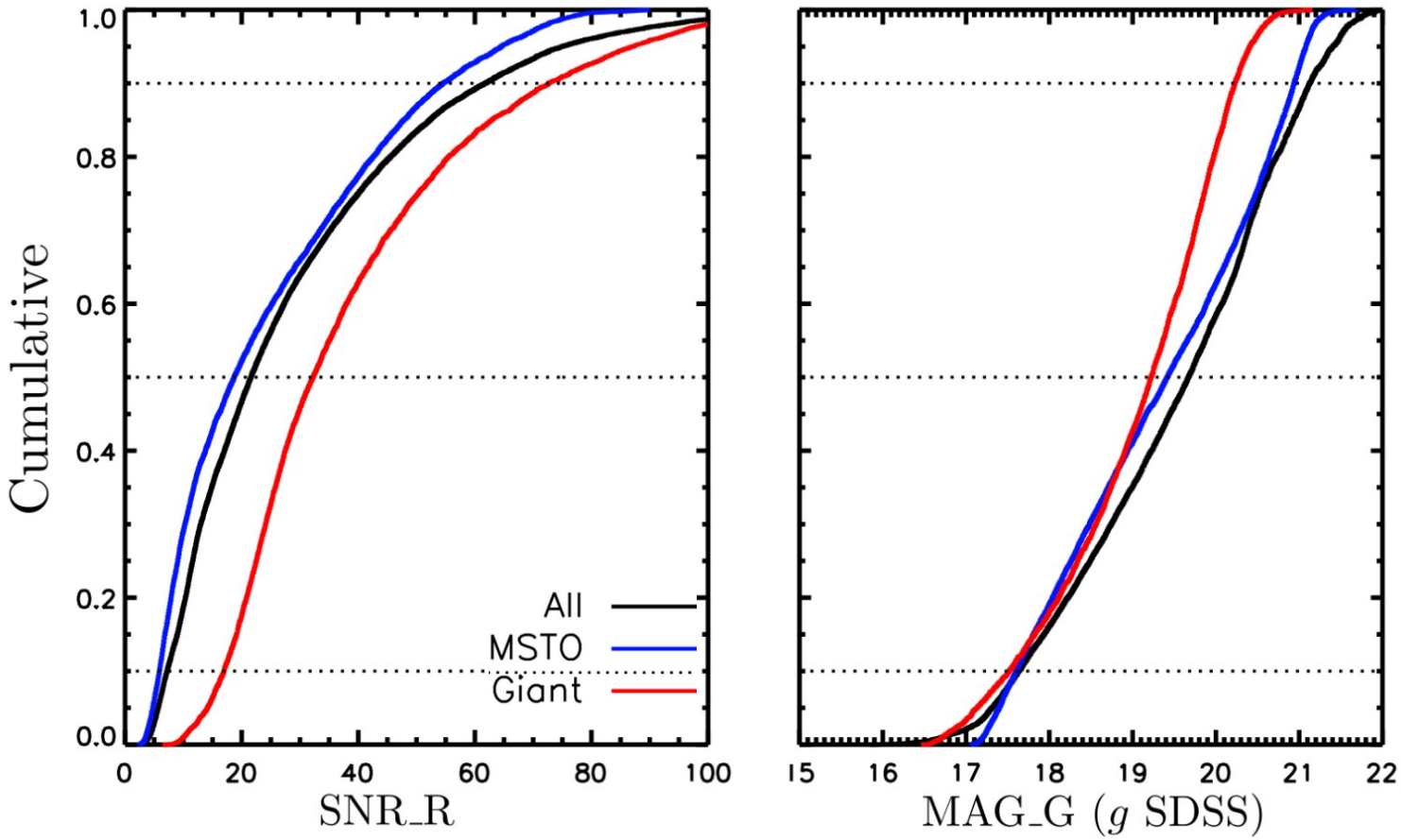


Figure from WEAVE Survey plan (v3.1)

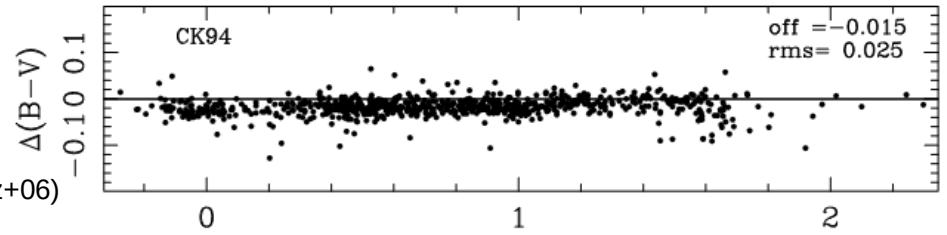
WEAVELIB Stellar Parameters

- WEAVE Advanced Processing System (APS):
  - Classifier
  - Stellar Module with FERRE algorithm (Allende-Prieto & Apogee Team 2015)

- LR spectra:
  - RVs
  - Main stellar parameters: Teff, log g, [M/H], [α/Fe]
    - Expected precisions for most stars:
      - Radial velocity: from ~1 to ~6 kms^{-1} (much better than GAIA RVS >4 kms^{-1})
      - Teff: from ~50 to ~150K
      - Logg: from ~0.1 to ~0.25 cms^{-2}
      - [M/H]: from ~0.15 to ~0.25 dex

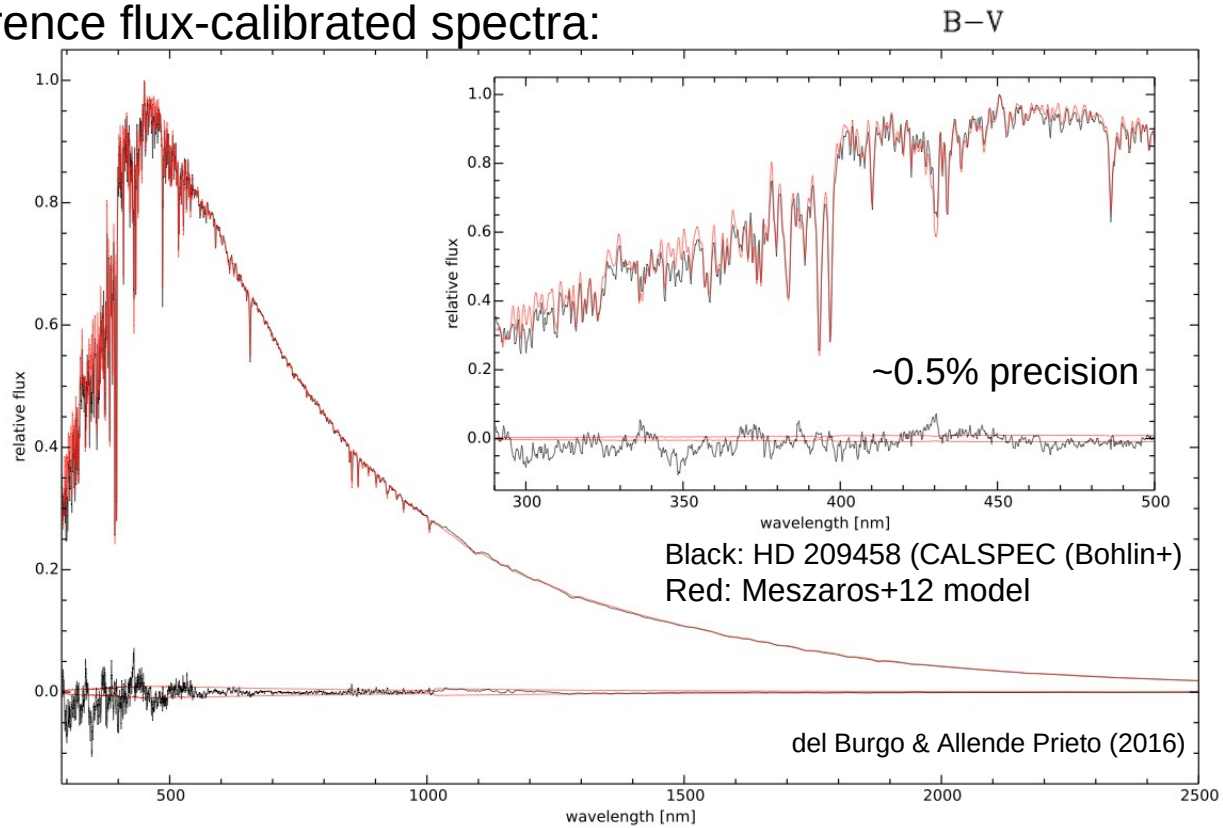
Flux-Calibration

Aimed precision: < 5%



MILES library (Sánchez-Blázquez+06)

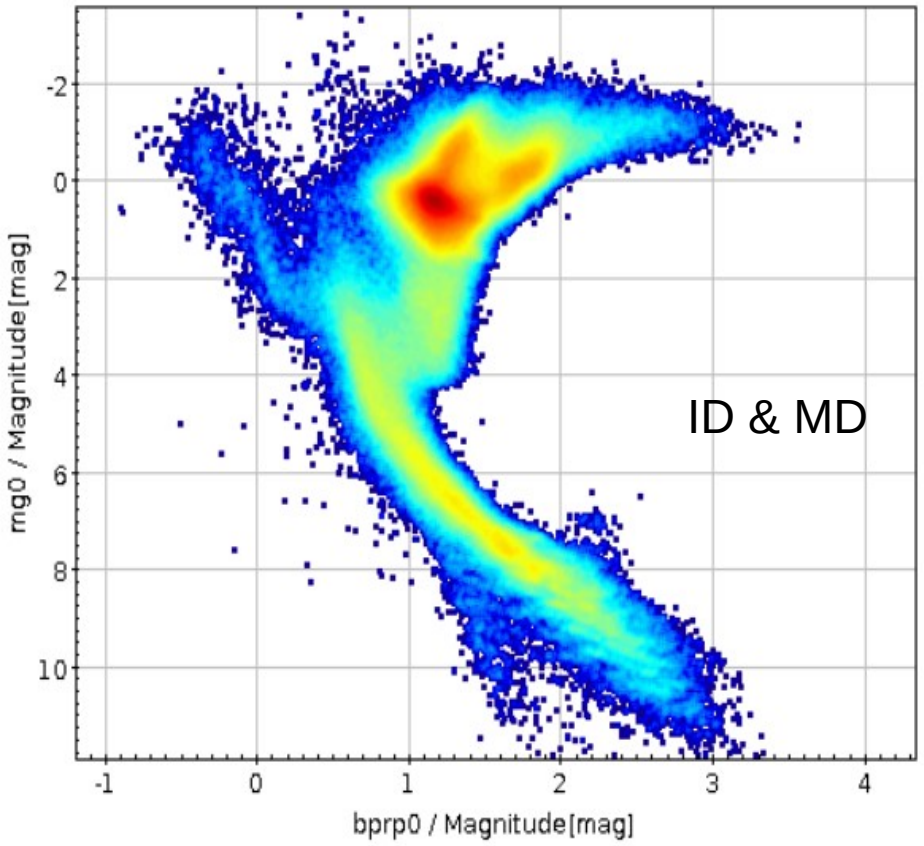
Use reference flux-calibrated spectra:

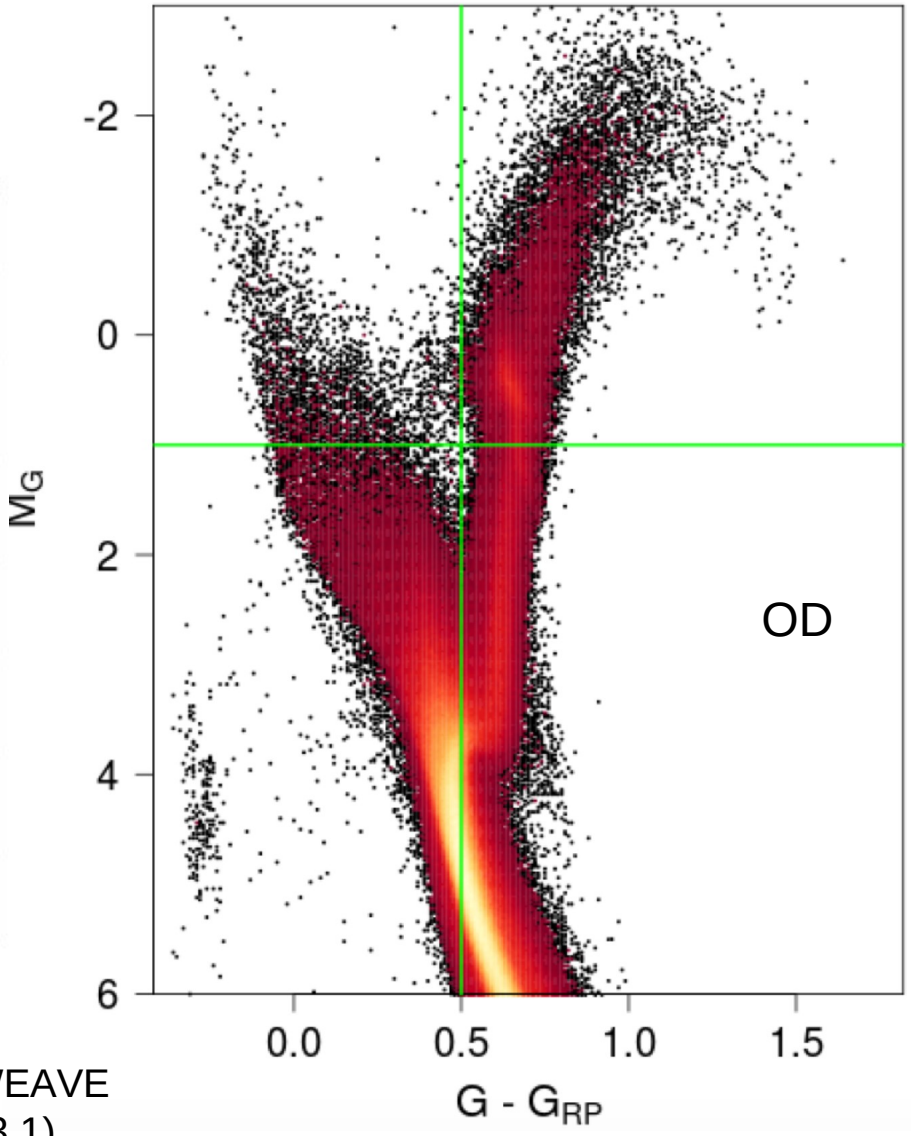


- Estimate: ~7% precision with XP Gaia (covering WEAVE range @ R~30-100)
- WEAVE white dwarf survey spectra can be used over the years.

GA: LR-disc

Expected HR diagrams
(good quality flags only):





Figures from WEAVE
Survey plan (v3.1)

Other WEAVE star surveys

- SCIP:
  - ~200000 AB stars + ~20000 OB stars
  - Parameters determination method (CaII Triplet region) (Simón-Díaz+10, Holgado+18, Carneiro +19)
- WD:
  - ~100000 WD candidates from Gaia DR2
- Galaxy-targeted surveys:
  - WEAVE StePS, WEAVE Apertif… (stars in the FOV's)

Young SSPs in the NIR

SMARTY & SO-SMARTY

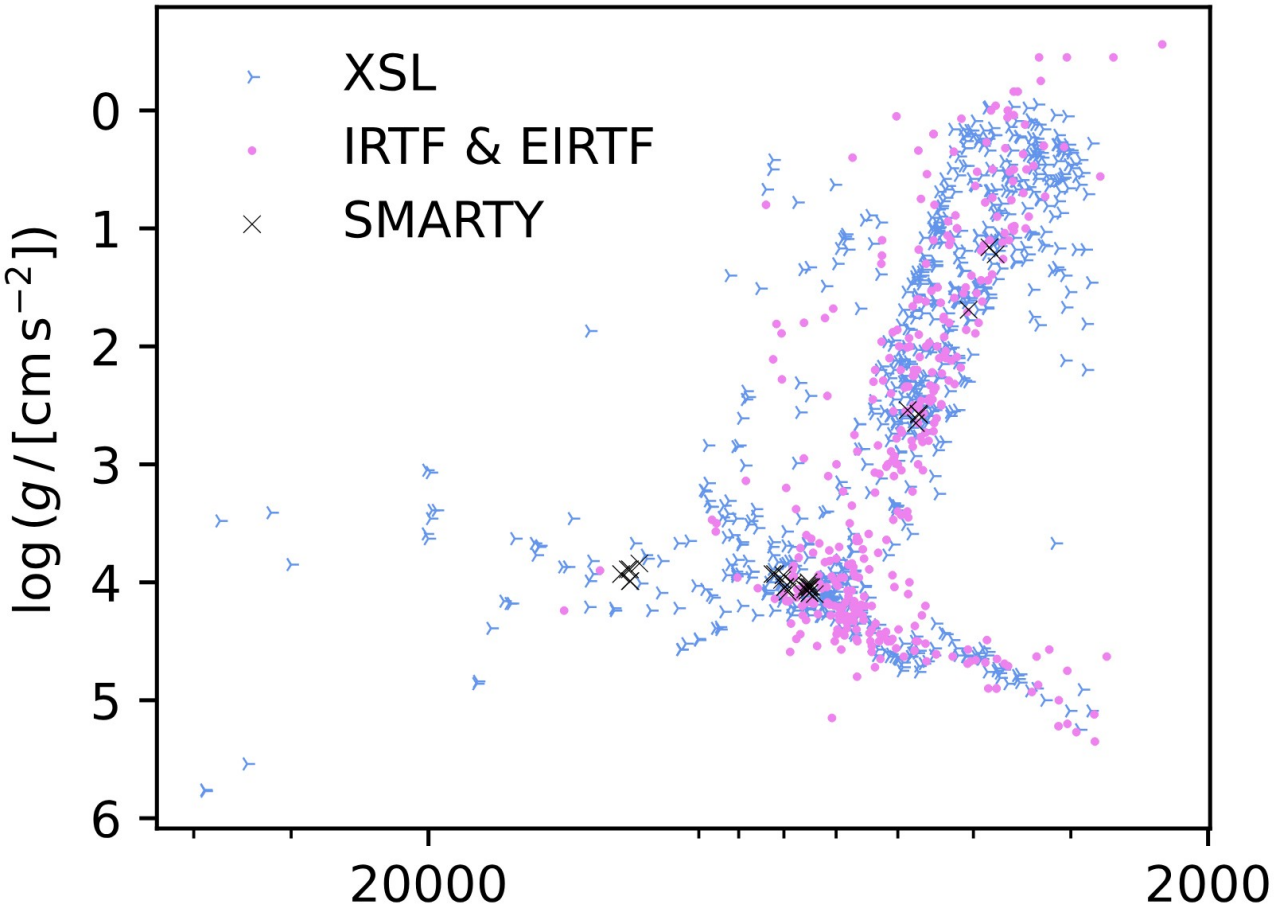
Bertoldo-Coelho, R. Riffel, M. Trevisan, N. Dametto, L. Dahmer-Hahn, P. Coelho, L. Martins, D. Ruschel-Dutra, A. Rodríguez-Ardila, A.L. Chies-Santos, R.A. Riffel, F. La Barbera, I. Martín-Navarro, J. Falcón-Barroso, T. Moura

SMARTY

(mileS Moderate resolution neAr-infRared sTellar librarY)

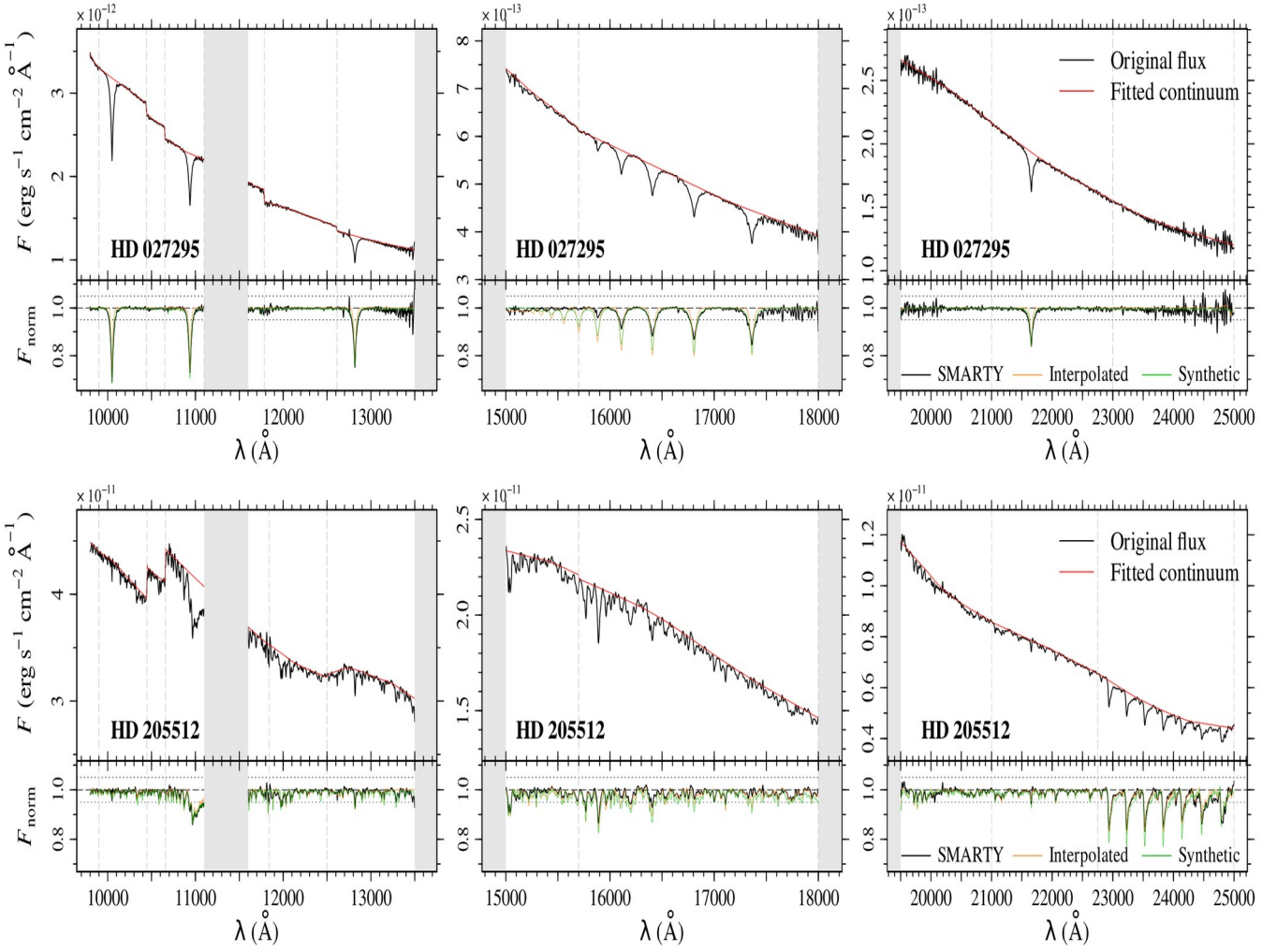
31 stars observed at Gemini (GNIRS):

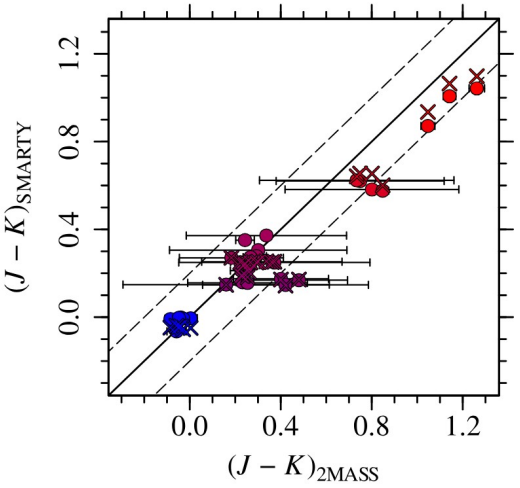
- 0.9−2.4 μm
- R~1300

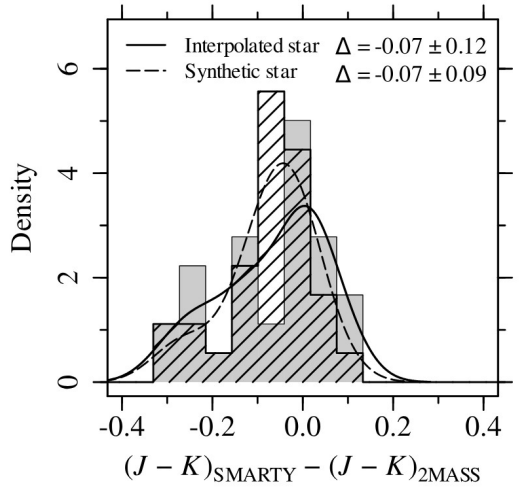


Bertoldo-Coelho+24

Continuum-corrected SMARTY spectra:



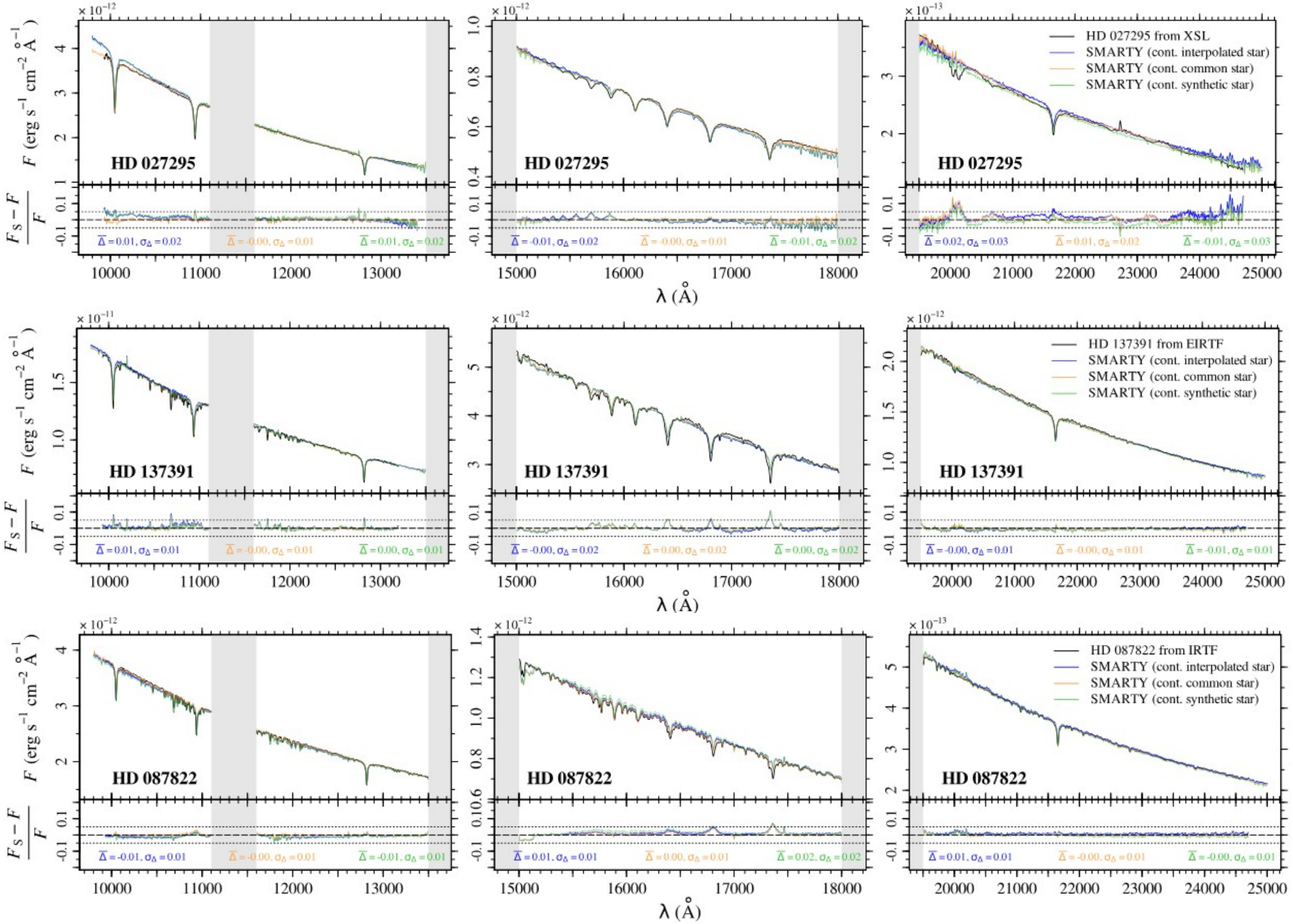




Bertoldo-Coelho+24

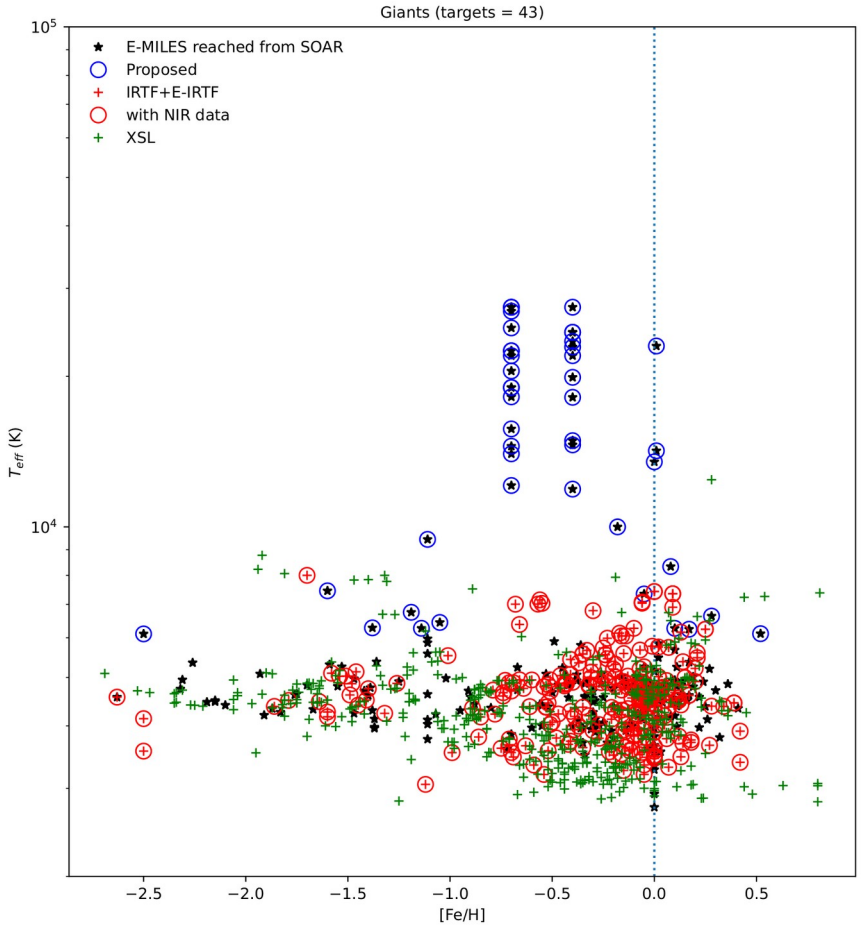
Common stars with IRTF & XSL:

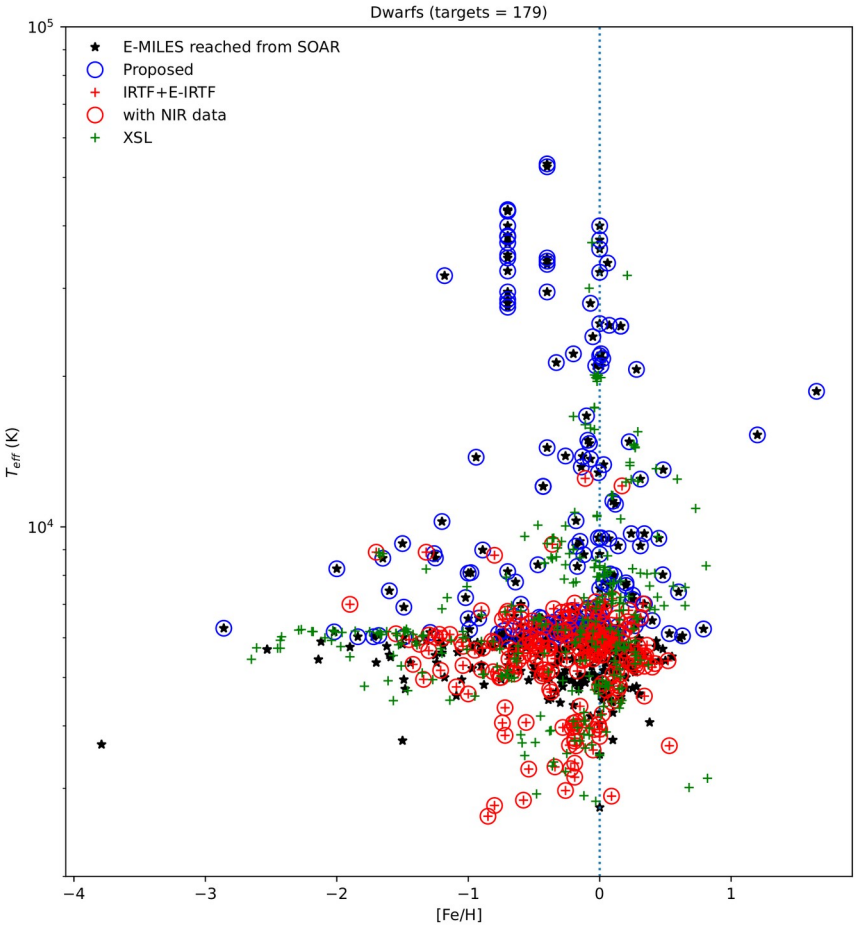
Bertoldo-Coelho+24



SO-SMARTY

- 222 stars ALREADY OBSERVED at SOAR (TripleSpec)
  - 1.0-2.47μm
  - R~3500
  - Stars with Teff>6000K






IAU Symposium 241
Stellar Populations
as Building Blocks of Galaxies