M giants with IGRINS:
Detailed exploration of the M giants near infrared spectra to chemically characterise the inner Milky Way

Govind Nandakumar
N. Ryde, G. Mace, M. Schultheis, R. M. Rich, L. Casagrande, B. Thorsbro

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LUND UNIVERSITY

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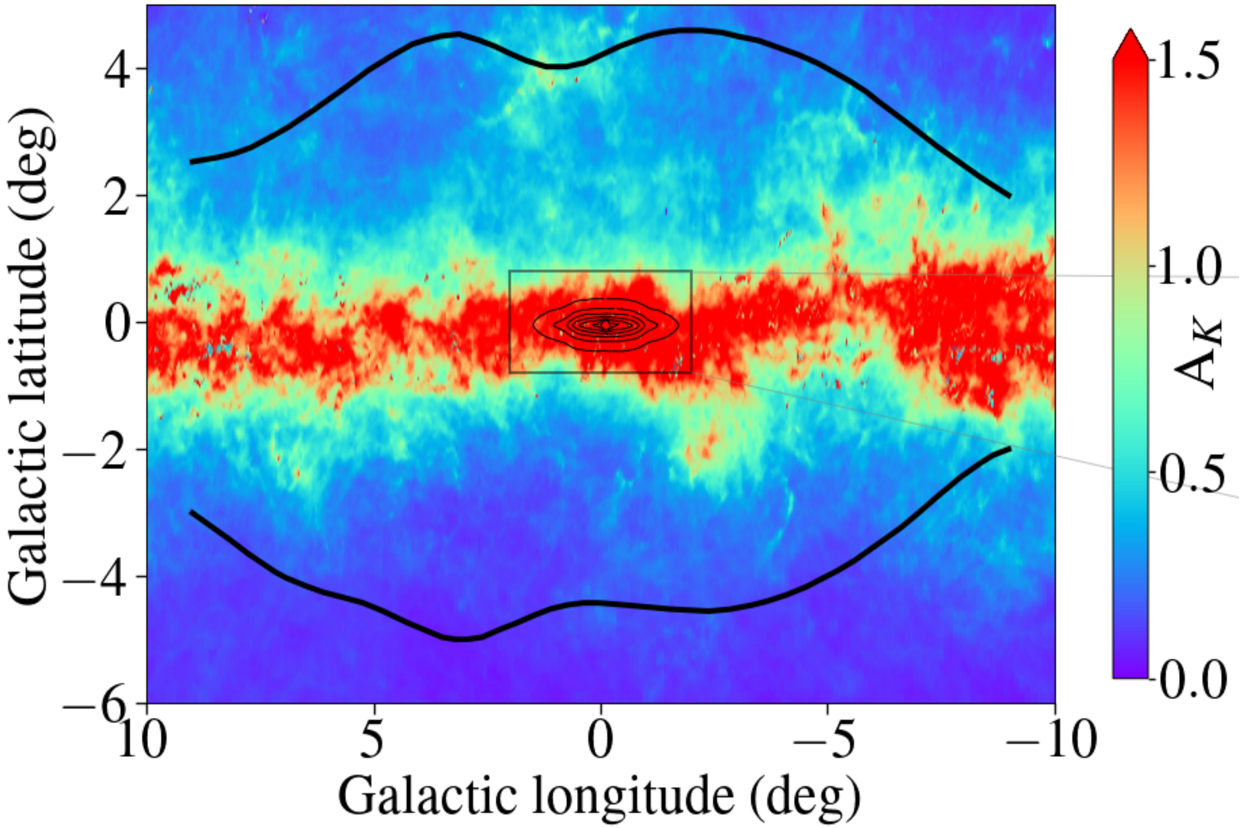
Inner Milky Way

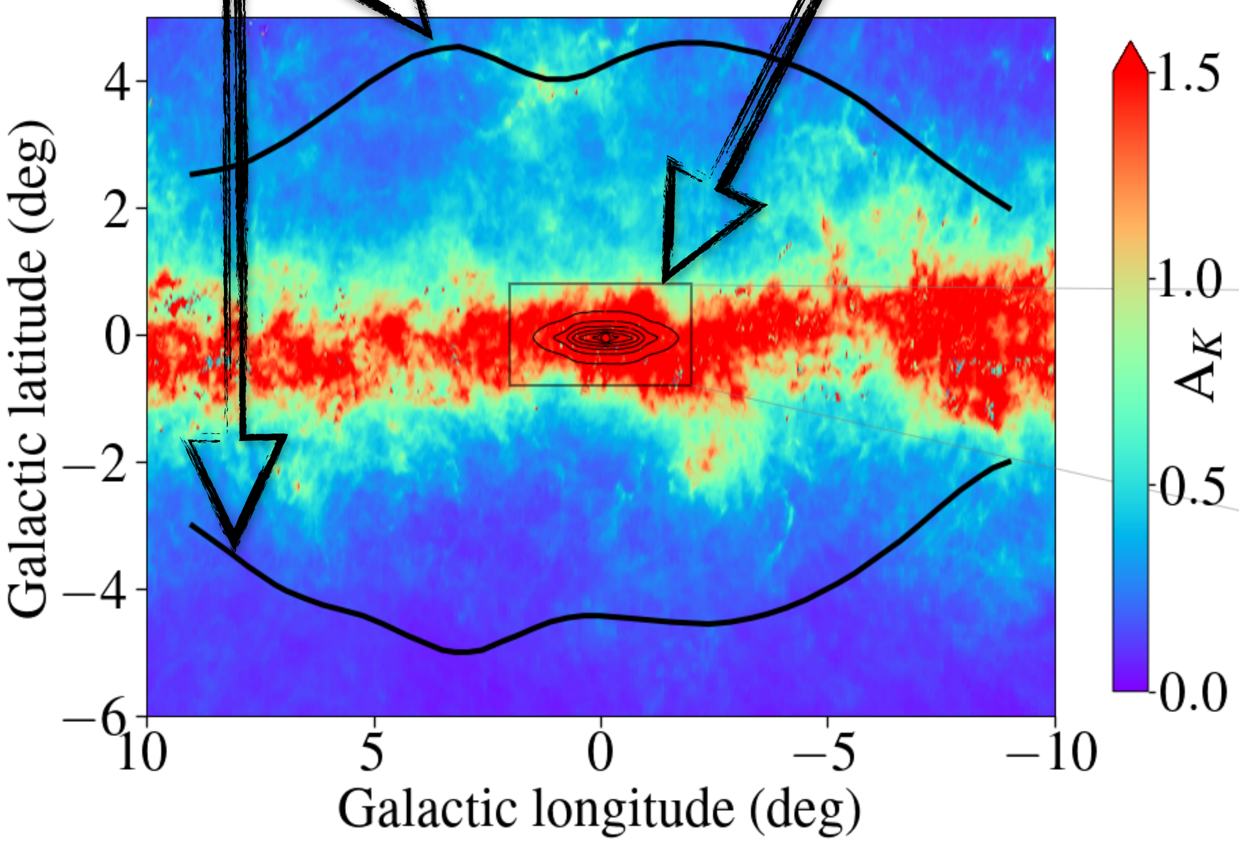


Mean A_K extinction map in the inner Milky Way, calculated from Gonzalez et al. (2012) using extinction coefficients from Nishiyama et al. (2009)

Inner Milky Way

COBE/DIRBE bulge envelope (Weiland et al. 1994)

Region encompassing the CMZ (Nandakumar et al. 2018a)



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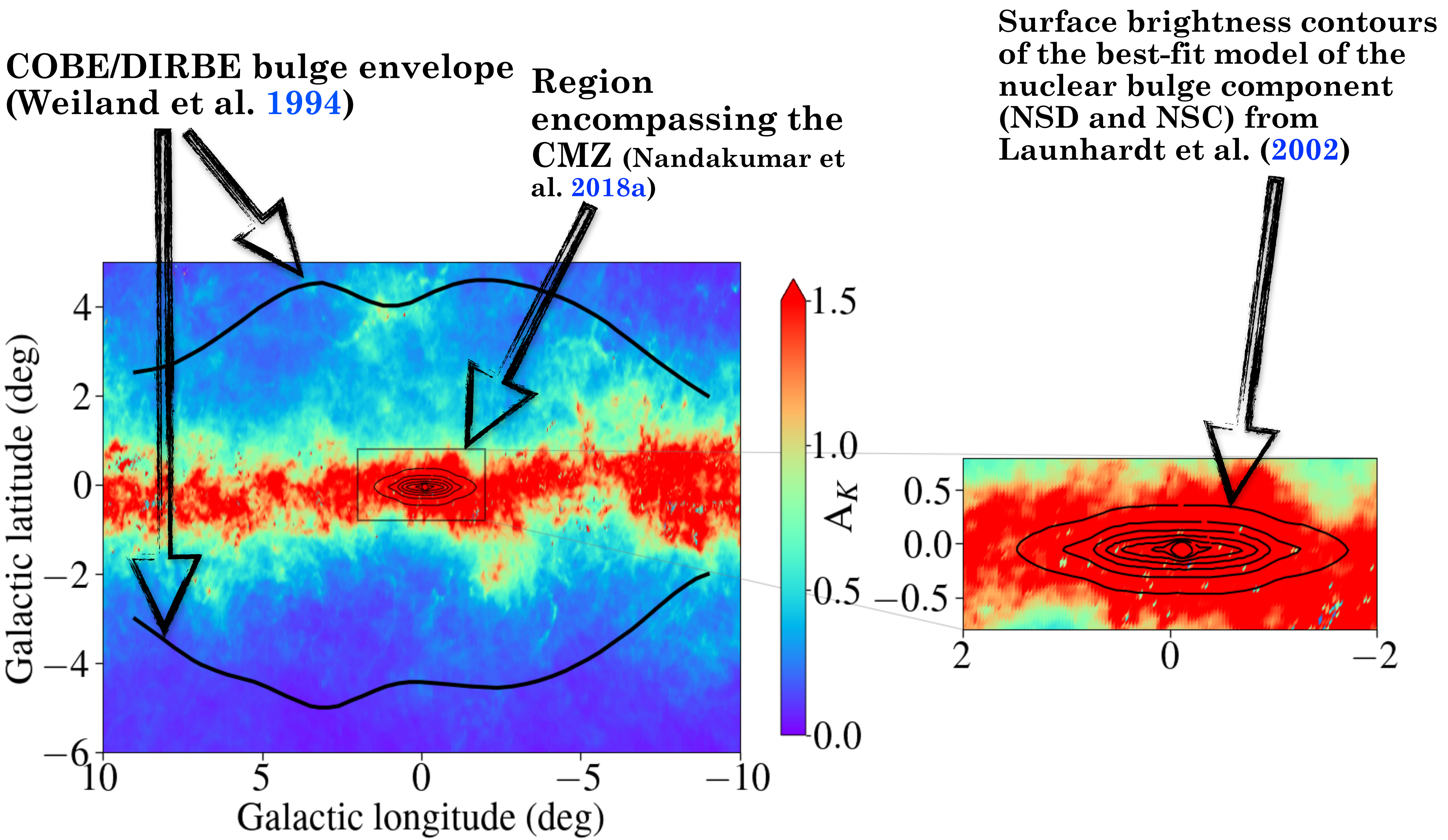

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Challenges

Dust / large extinction → Near IR wavelength regime

Near IR spectra → Not as explored as optical spectra

Large distance (~ 8 kpc) → Bigger telescopes and longer exposures

Observable stellar populations → K/M giant stars (Teff < 4000 K)

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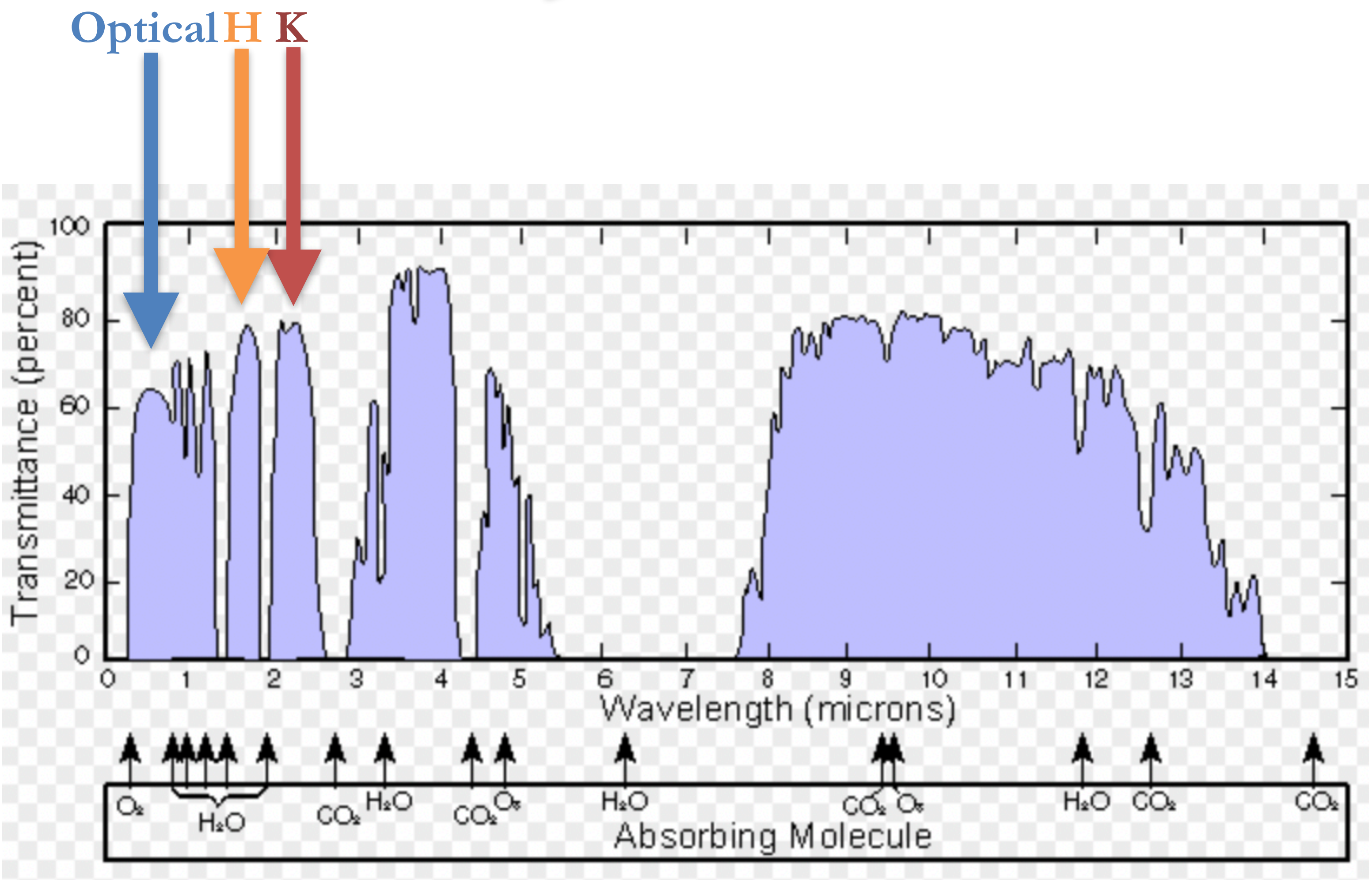

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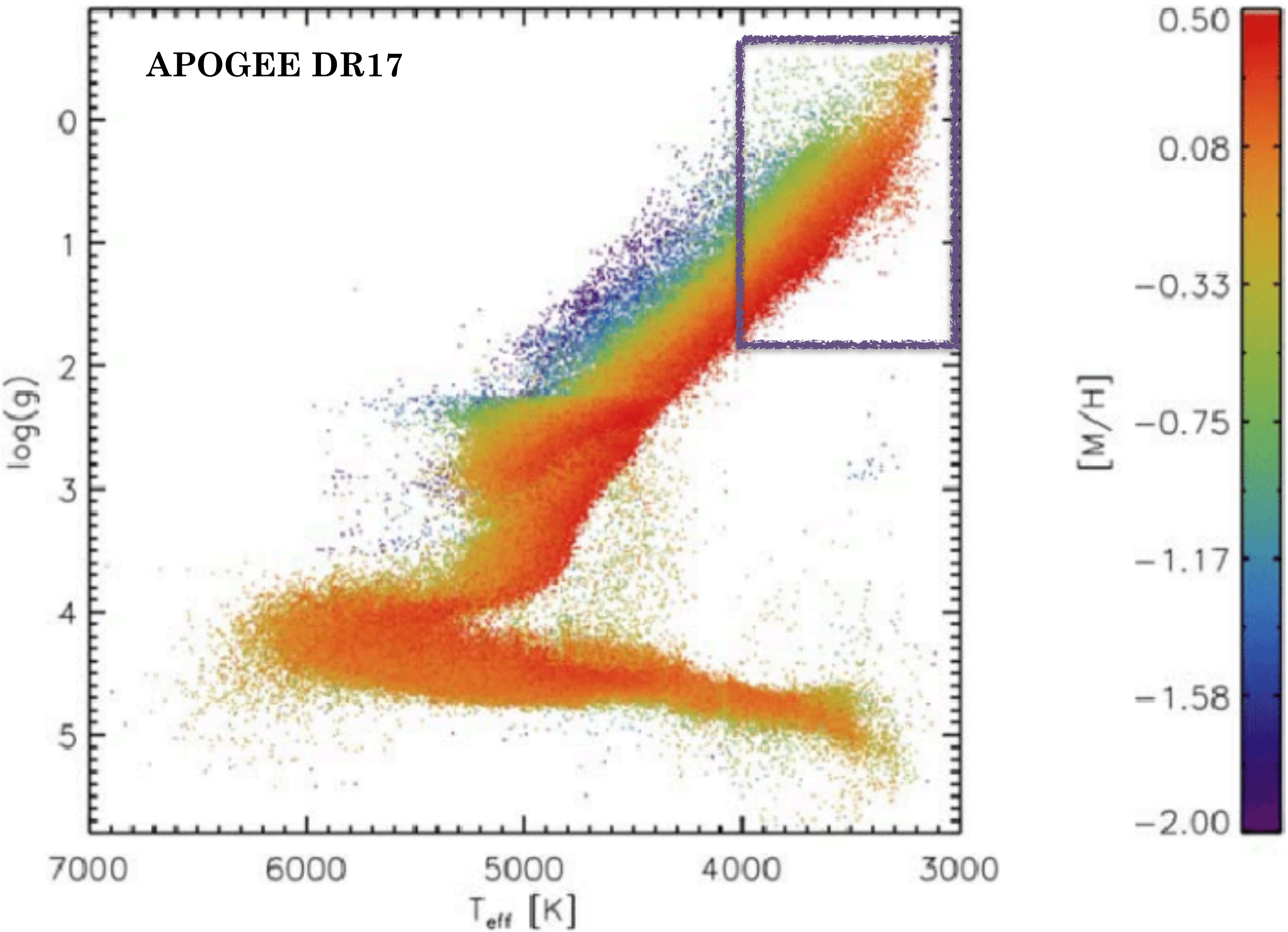

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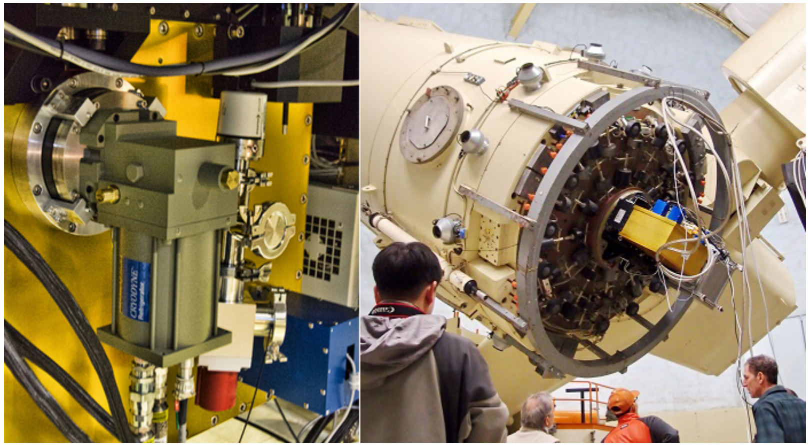
- Consistent and systematic analysis of inner Milky Way stars : observe with the same instrument, and analyse with same method and spectral lines.

Instrument

- Immersion Grating Infrared Spectrograph (IGRINS; Park et al. 2004)
  R~ 45,000
  λ ~ full H and K bands (14500 - 24600 Å)



IGRINS on the 107” at McDonald Observatory
(Harlan J. Smith Telescope)

- Reduction using IGRINS PipeLine Package (Lee et al. 2017)

- Analysis with SME (Valenti & Piskunov 2012, 1996) and MARCS models (Gustafsson et al. 2008)

- NLTE grids for Fe,C, N, O, Na, Mg, Al, Si, K, Ca, Mn, Ba (Amarsi et al. 2020)

Existing methods for T*eff* determination

- Interferometry (Mozurkevich et al. 2003)
- Infrared flux method (IRFM; Casagrande et al. 2008)
- Color-T*eff* relations (Bessel et al. 1998)

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Need a method to determine T*eff* directly from spectra:

- Line depth ratios between high and low excitation energy lines (Afsar et al. 2023)- **Affected by metallicities**
- CO bandhead in low resolution spectra - **Not precise enough**
- Sc line in the K-band (Thorsbro et al. 2020) - **Promising**
- APOGEE-type full spectral fitting - **Not validated for cool stars**

T*eff* sensitive near-IR lines

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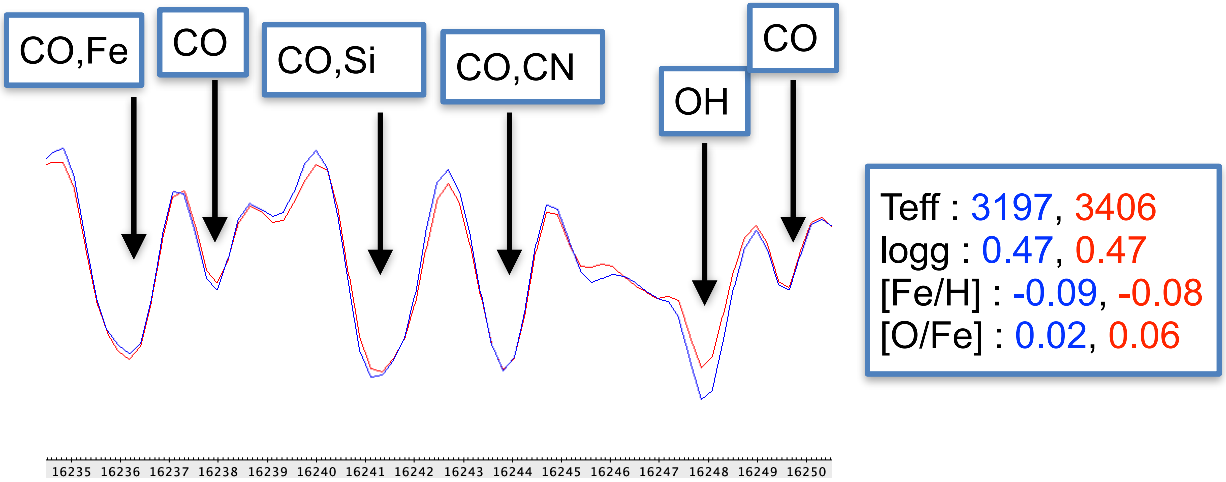

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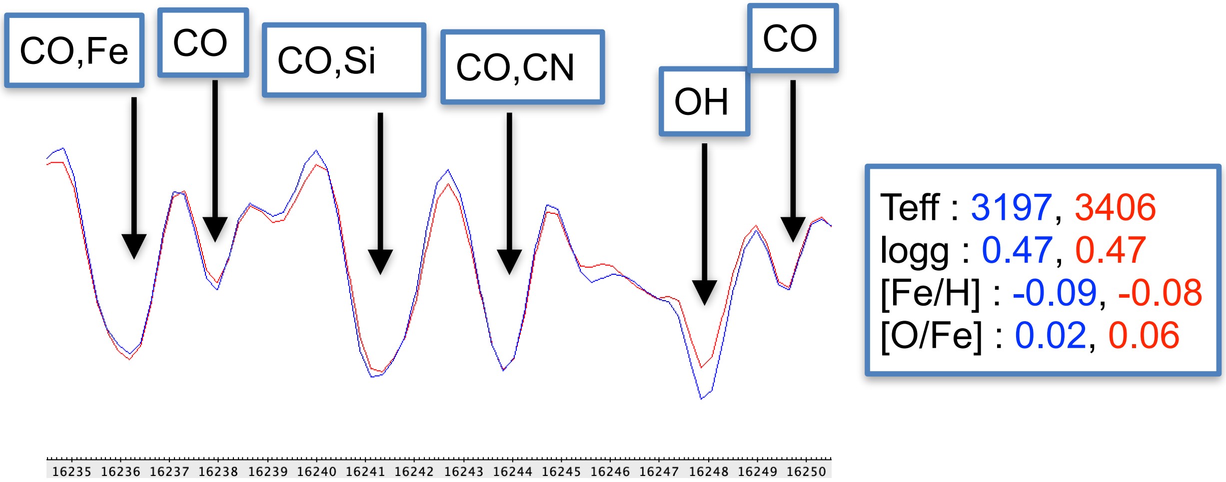

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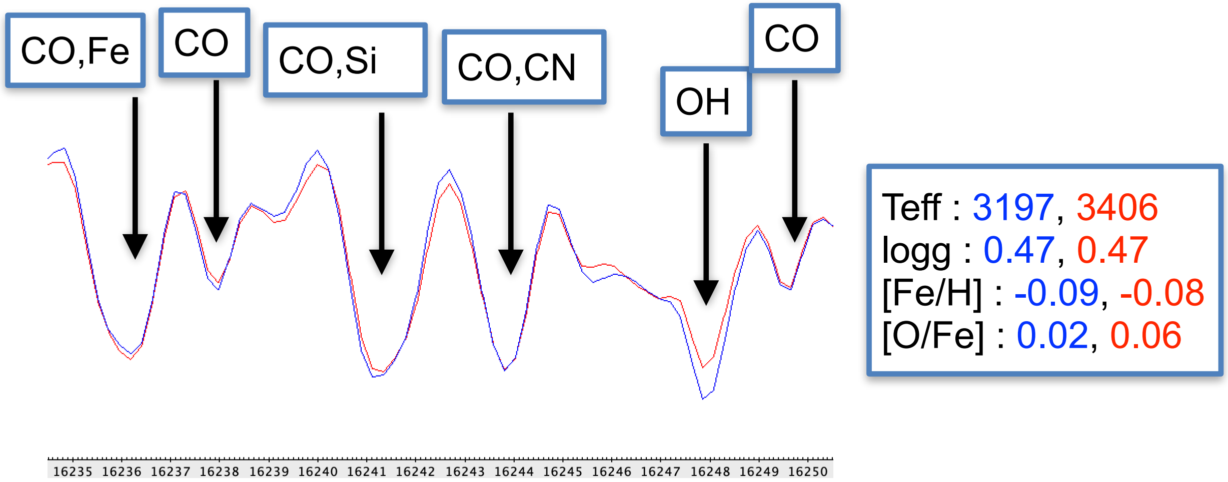

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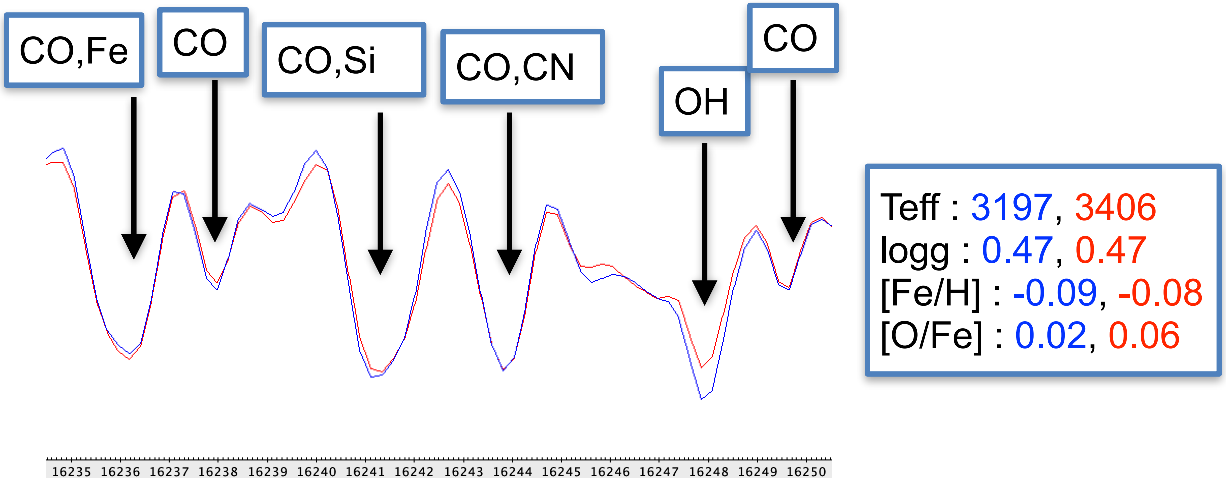

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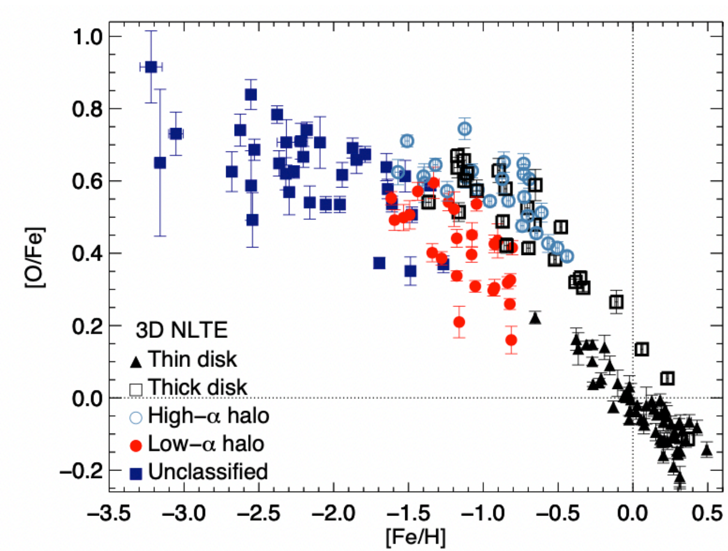

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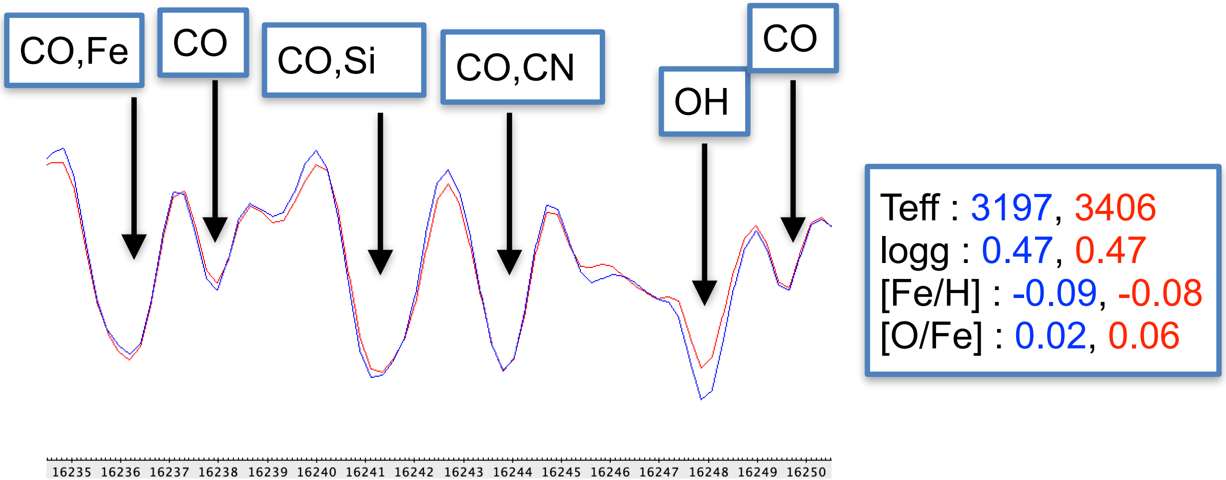

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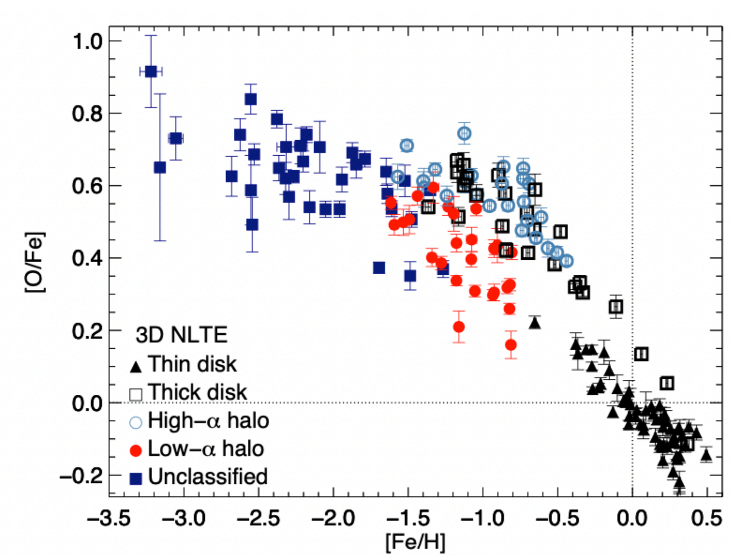

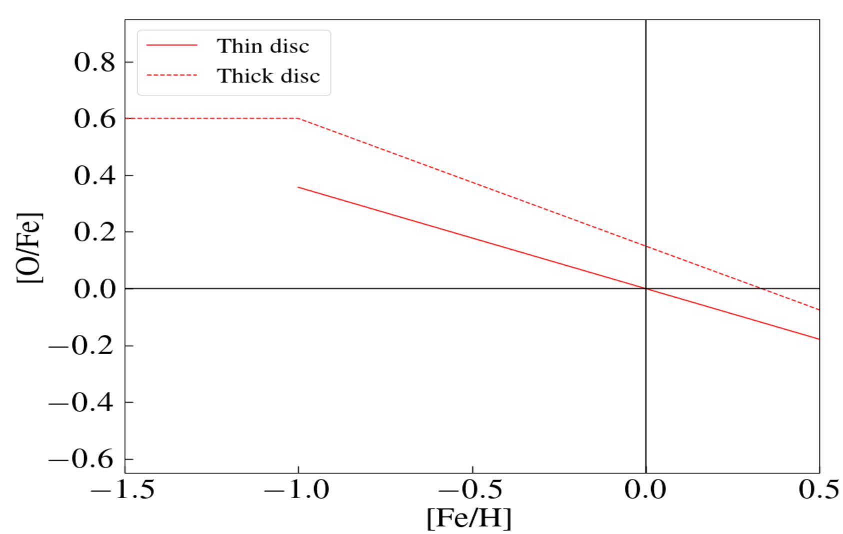

Method

Teff = 3500 K
logg = 0.65 dex
[Fe/H] = 0.0 dex
χ_{mic}= 1.87 km/s
[O/Fe] from Amarsi thin/thick disc

Nandakumar et al. (2023a)

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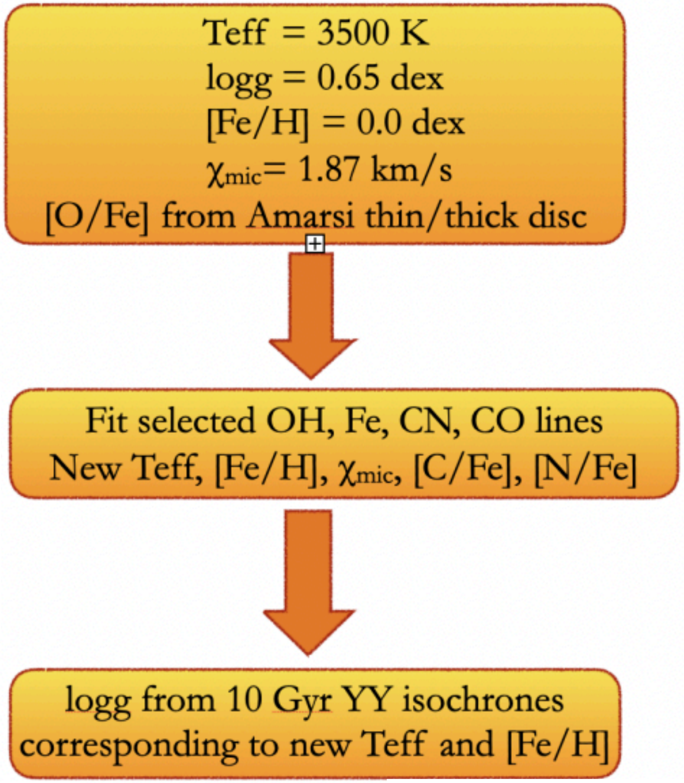
Fit selected OH, Fe, CN, CO lines
New Teff, [Fe/H], χ_{mic}, [C/Fe], [N/Fe]

Nandakumar et al. (2023a)

Method



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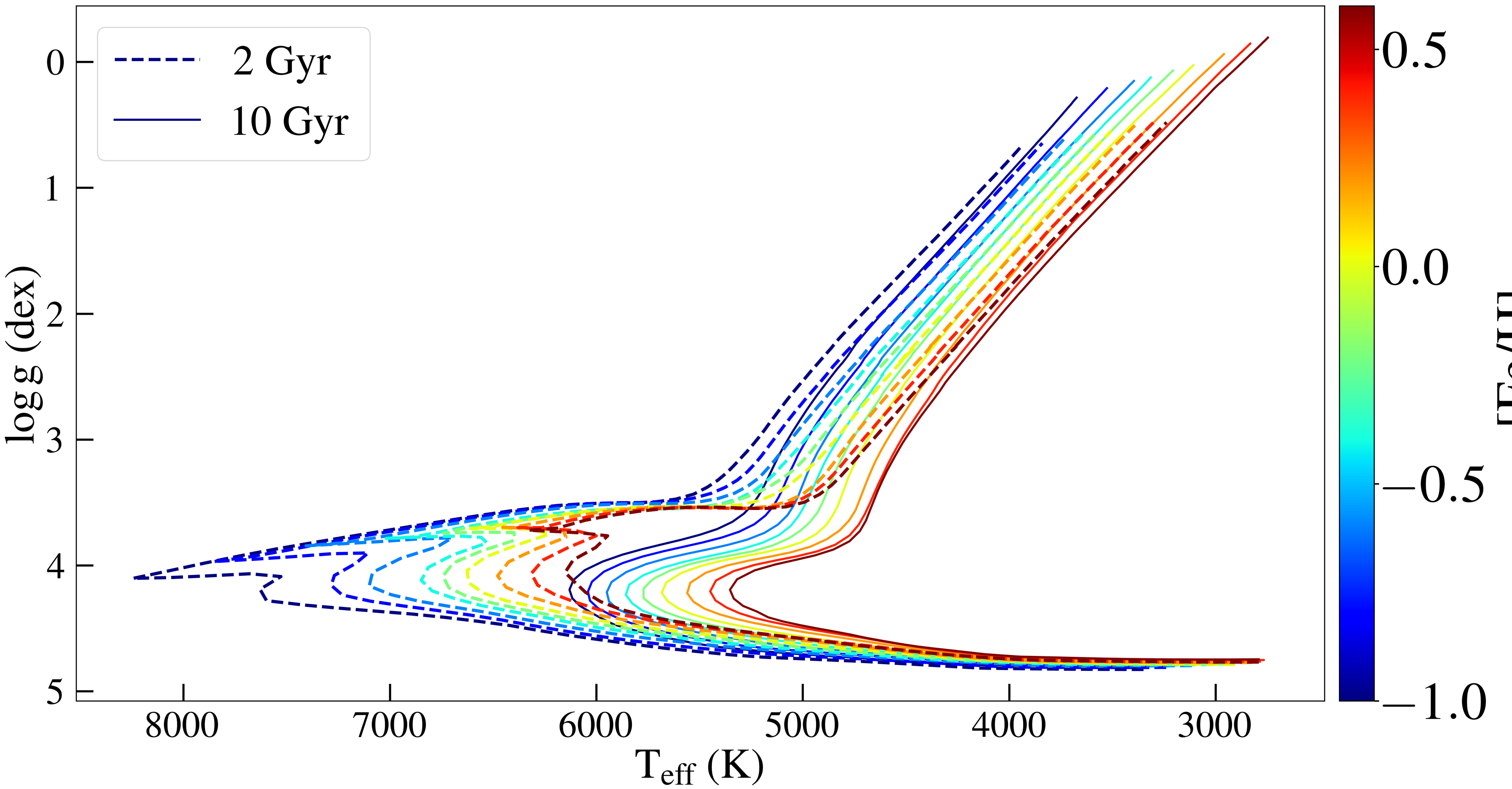

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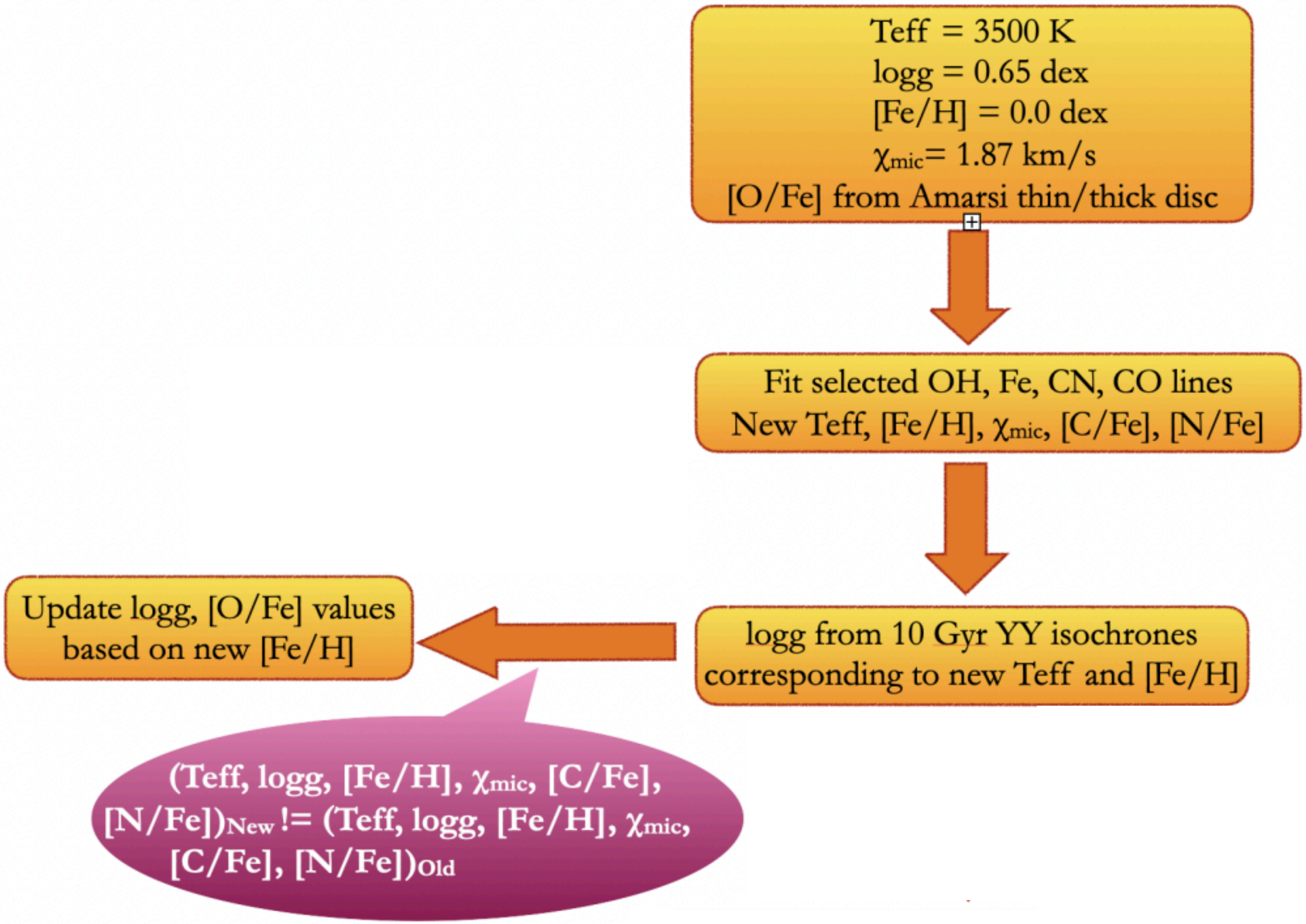

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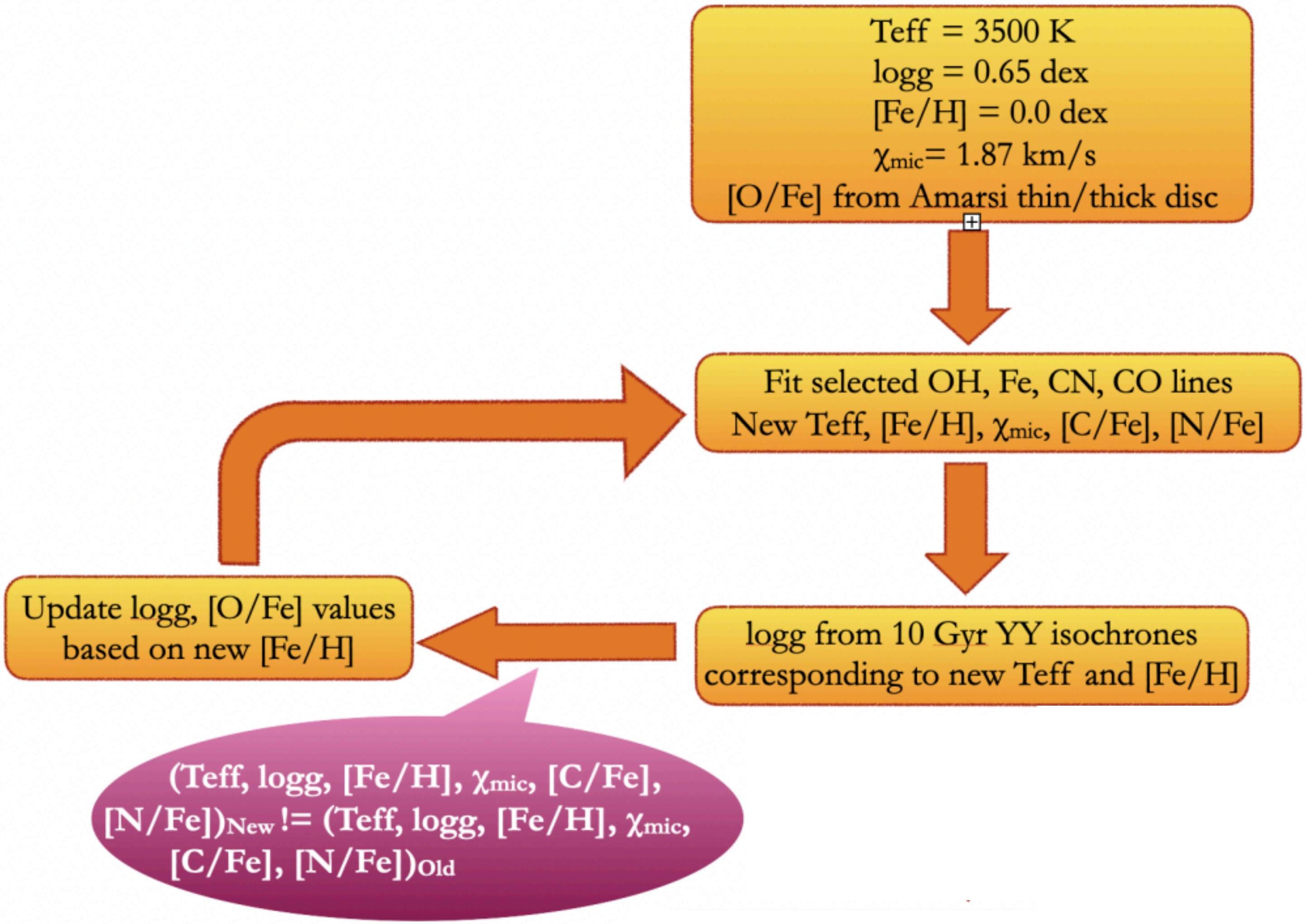

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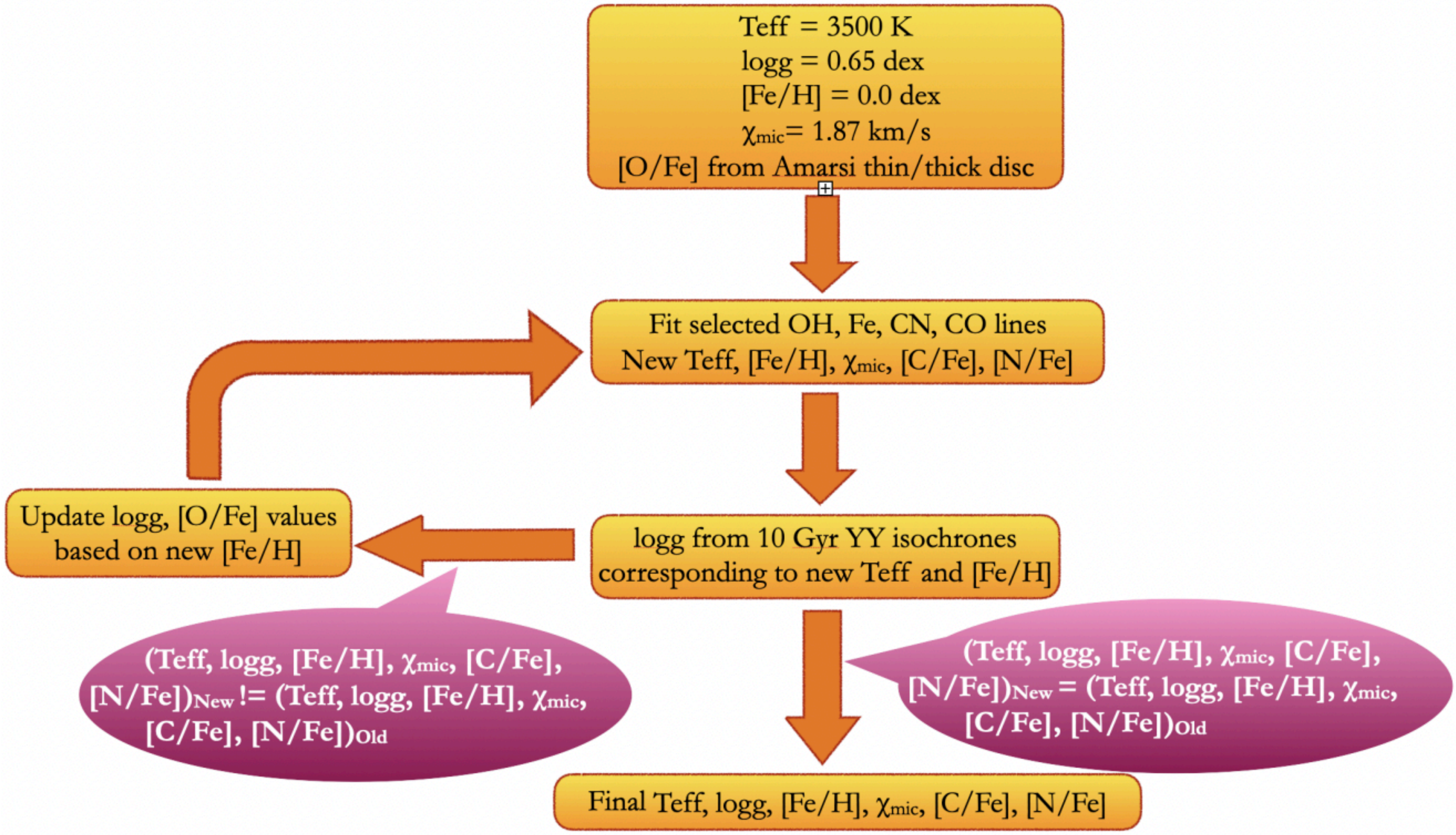

Nandakumar et al. (2023a)

Stellar parameters for M giants

- Sample: 6 nearby M giants with angular diameter Teff (spectral library)
  44 solar neighbourhood M giants (poor weather proposal)

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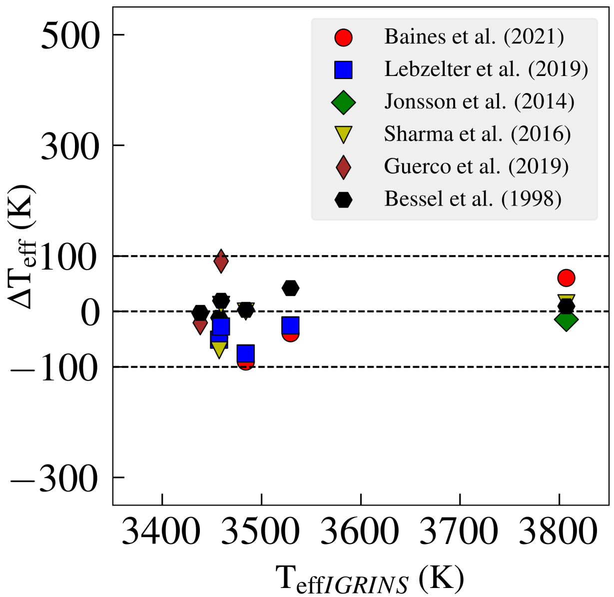

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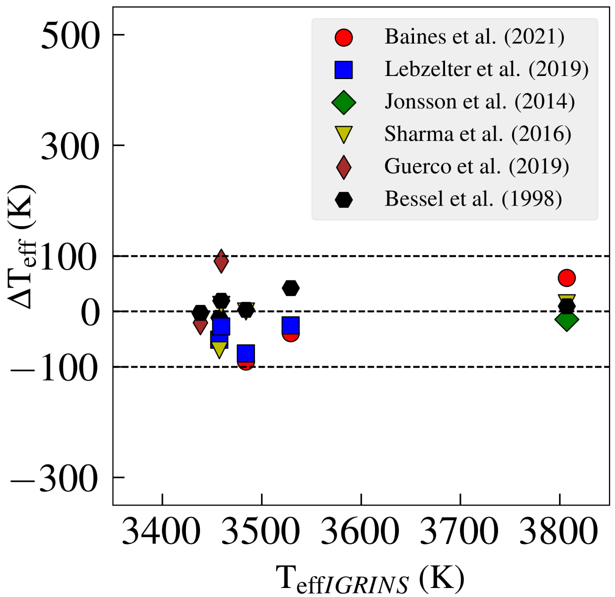
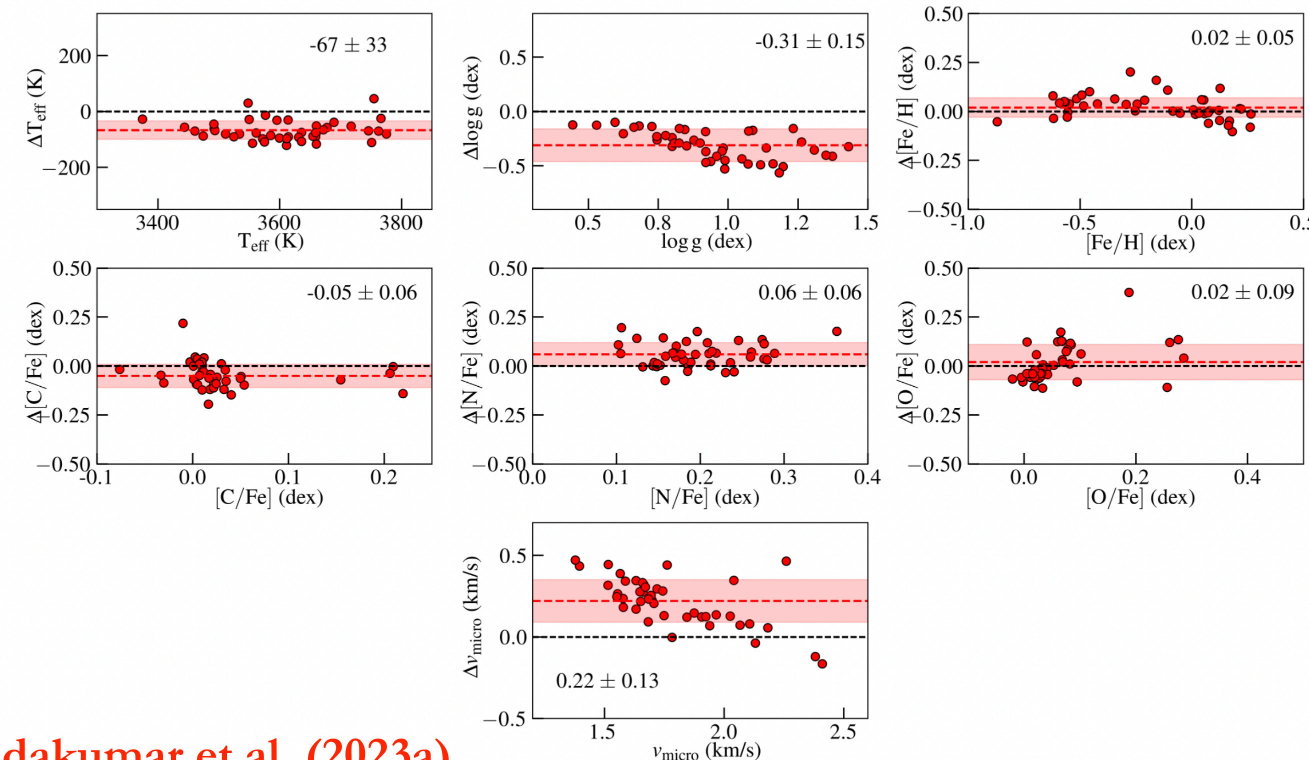


Y axis : Our method - APOGEE **X axis** : APOGEE



Nandakumar et al. (2023a)

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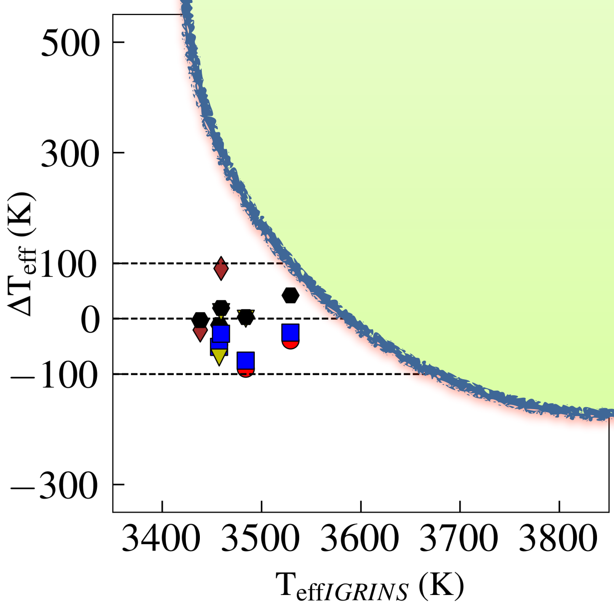
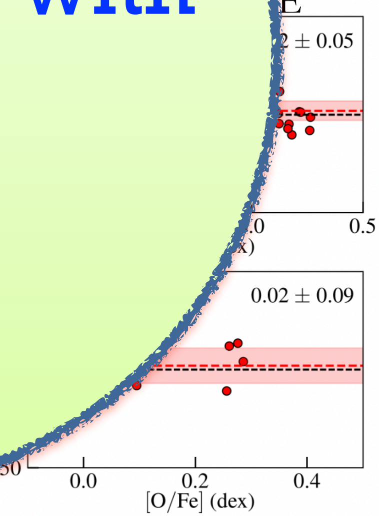
  44 so ... proposal)

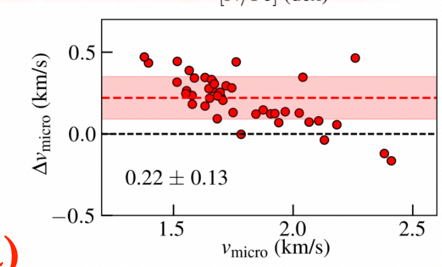
- Meth ... et al.
  202

50 solar neighbourhood M giants with IGRINS spectra

Y ax
X ax





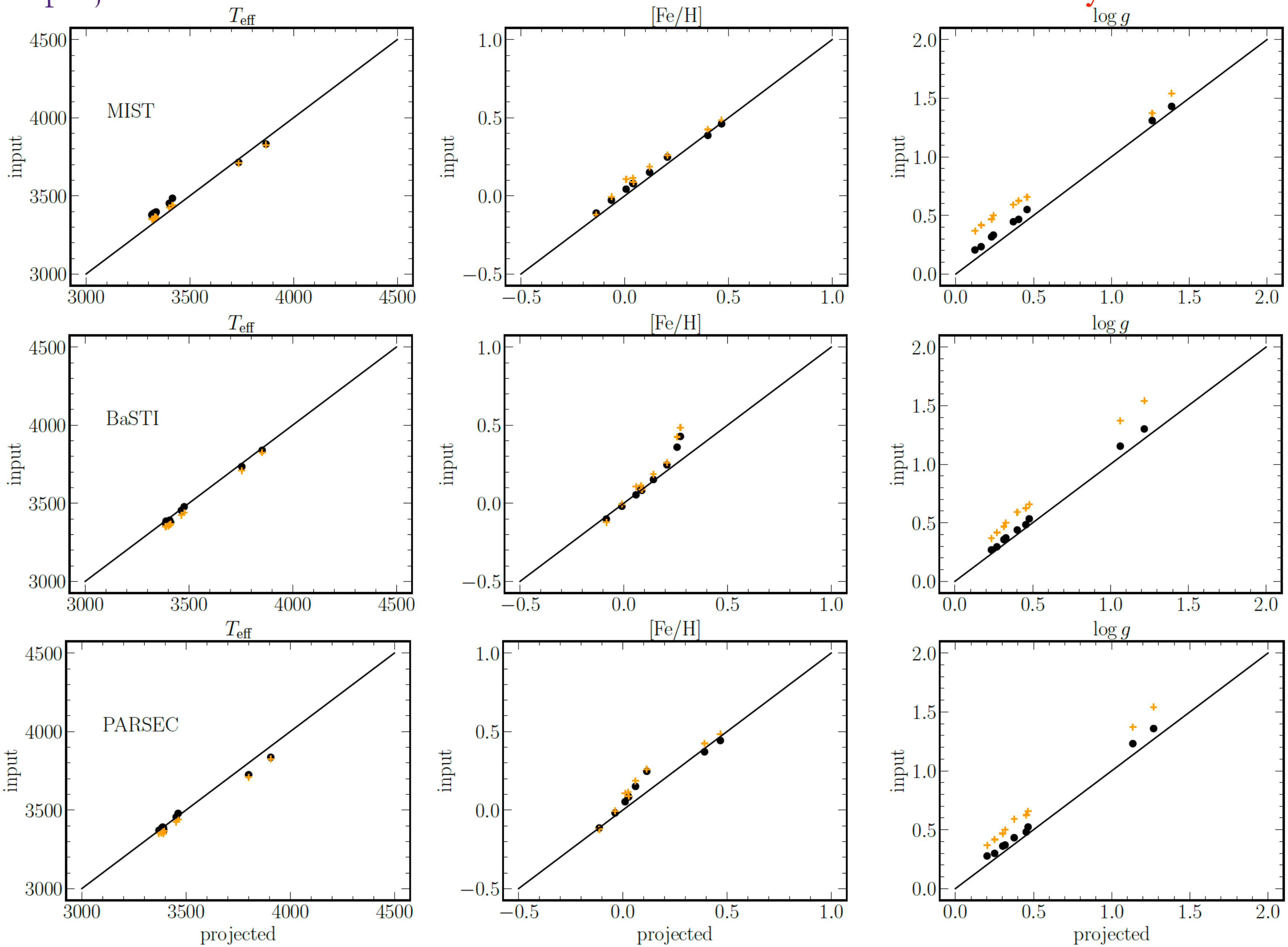


Nandakumar et al. (2023a)

Impact of iscochrone choice

+ First projection
● Second projection

Kordopatis et al. (2023a)
Ryde et al. submitted



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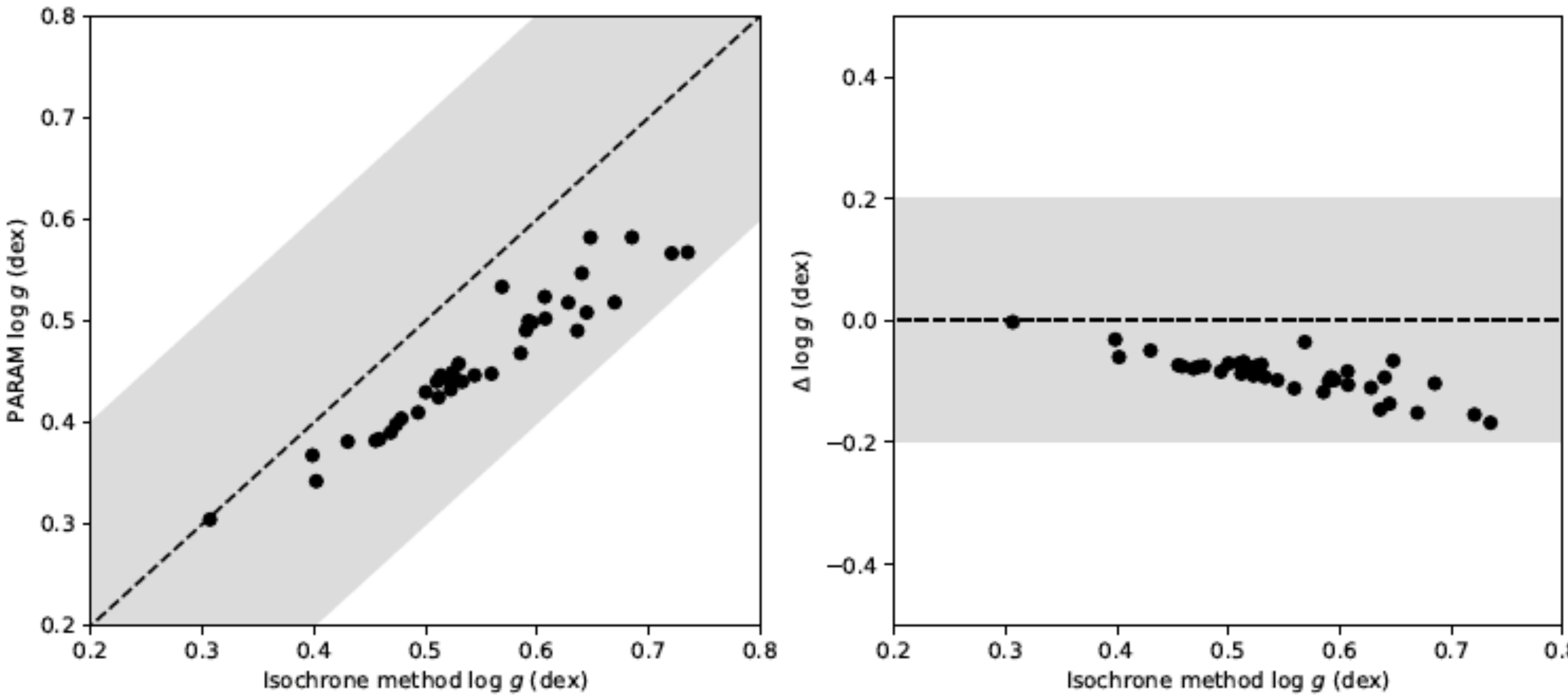
Comparison with PARAM surface gravities (MESA)



Kocher, J. 2024

http://stev.oapd.inaf.it/cgi-bin/param

Goals

- Develop method to determine stellar parameters of M giant stars from near-IR spectra
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  P (Nandakumar et al. 2022)
  Yb (Montelius et al. 2022)
  F (Nandakumar et al. 2023b)
  Ba (Nandakumar et al. 2024c)
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Other elements

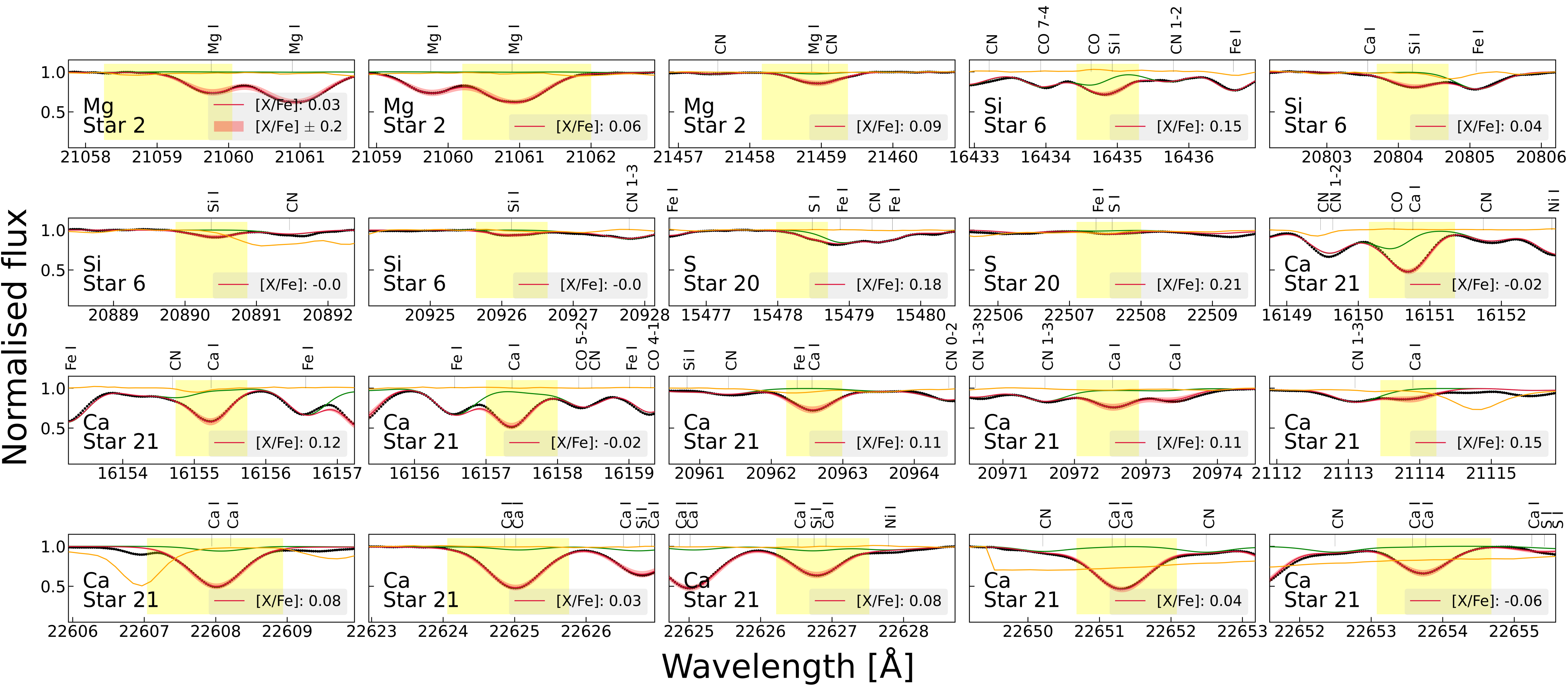
Observed spectra

Synthetic spectra

Telluric spectra

No element

Alpha elements



Nandakumar et al. (2024b)

Other elements

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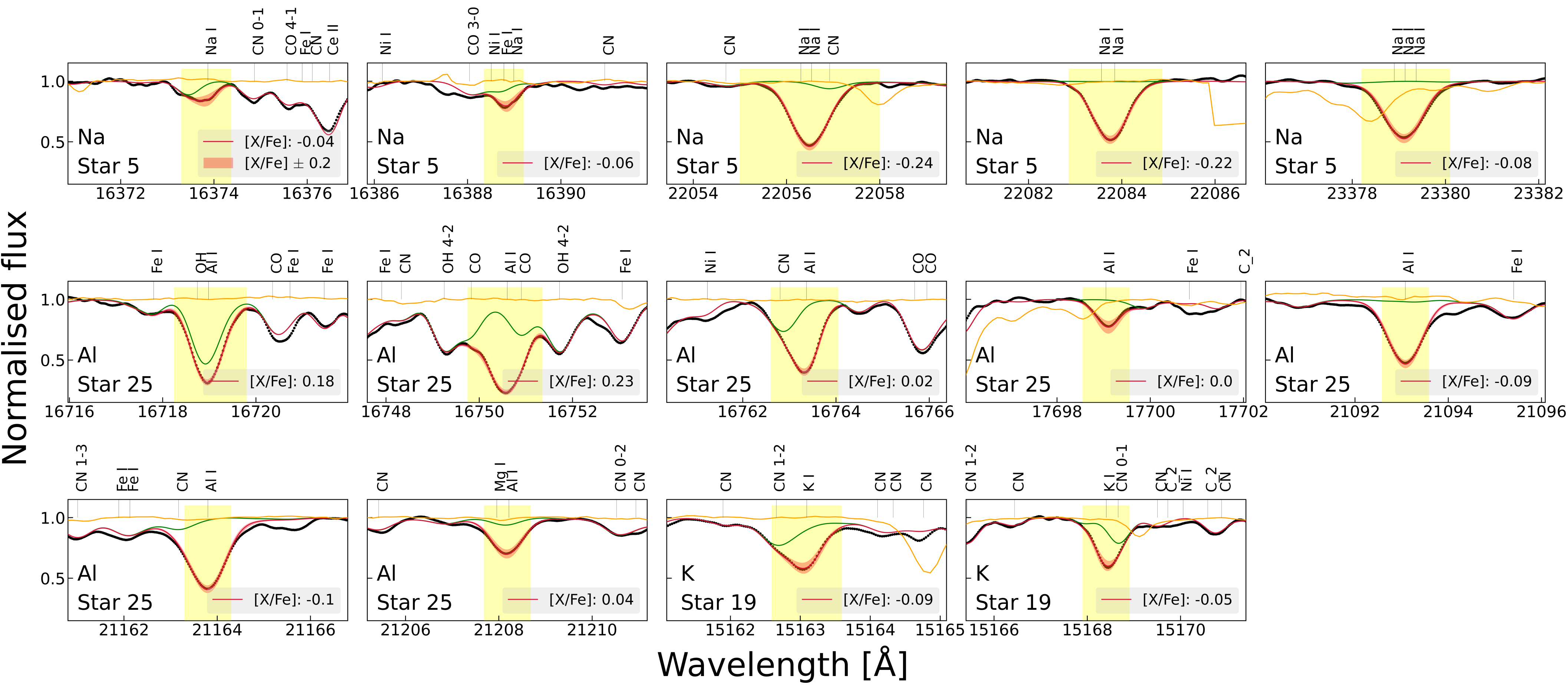
Synthetic spectra
Telluric spectra
No element

Odd-Z elements



Nandakumar et al. (2024b)

Other elements

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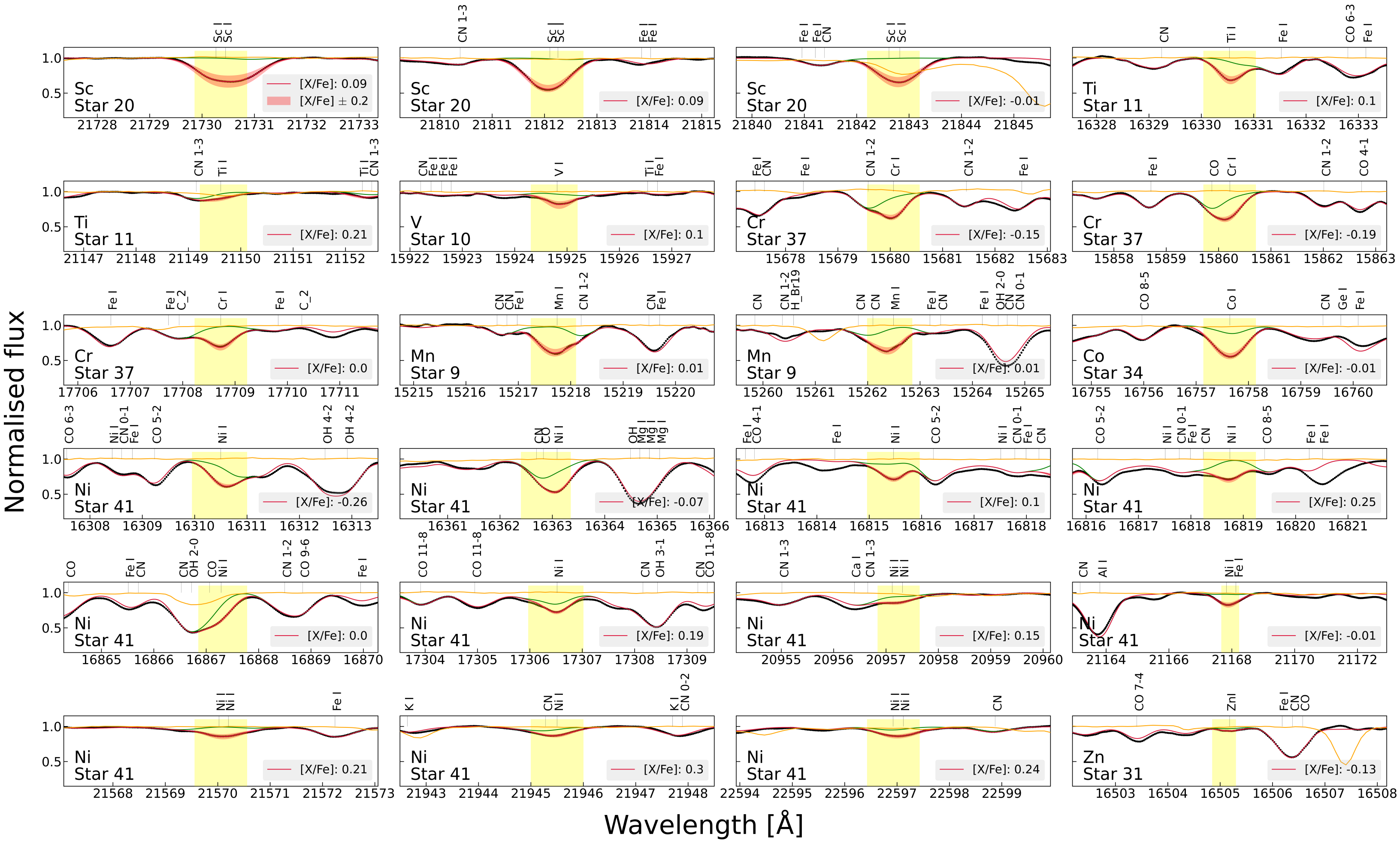
Telluric spectra

No element

Iron-peak elements



Nandakumar et al. (2024b)

Other elements

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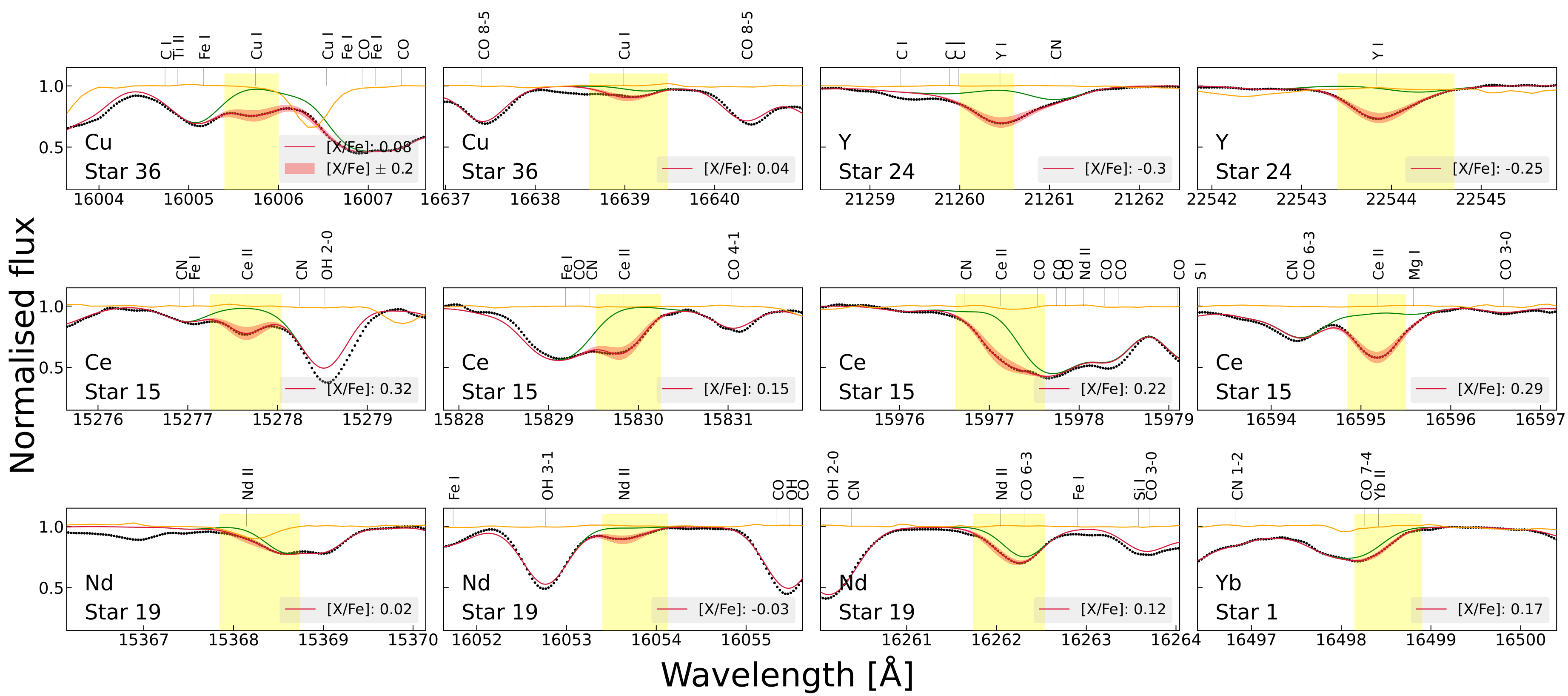
No element

neutron-capture elements



Nandakumar et al. (2024b)

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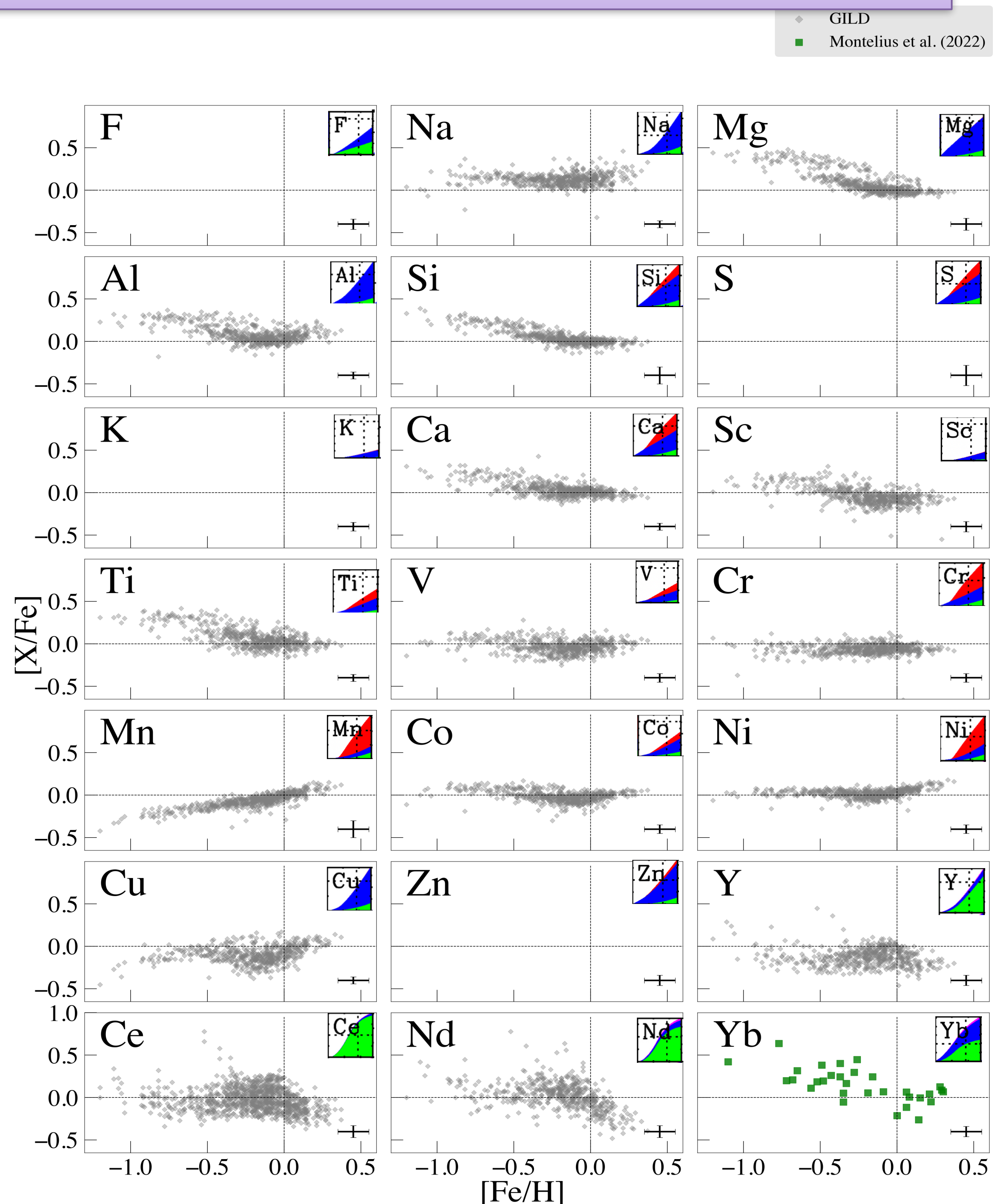
Abundance trends: 21 elements

Nandakumar et al. (2024b)



Asymptotic Giant Branch Stars
Core−collapse Supernovae
Type Ia Supernovae
Neutron Star Mergers

Kobayashi (2020)

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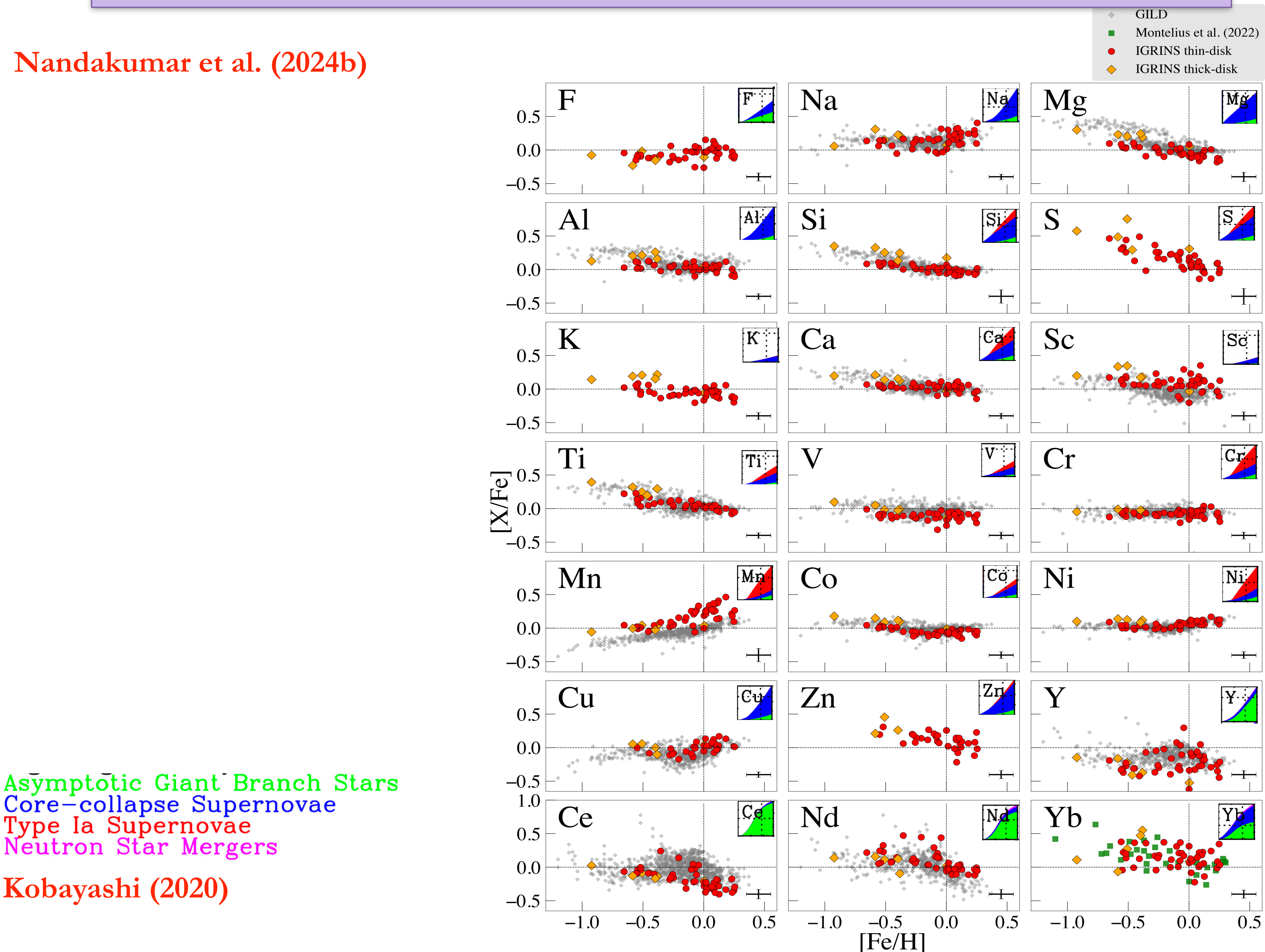
Nandakumar et al. (2024b)



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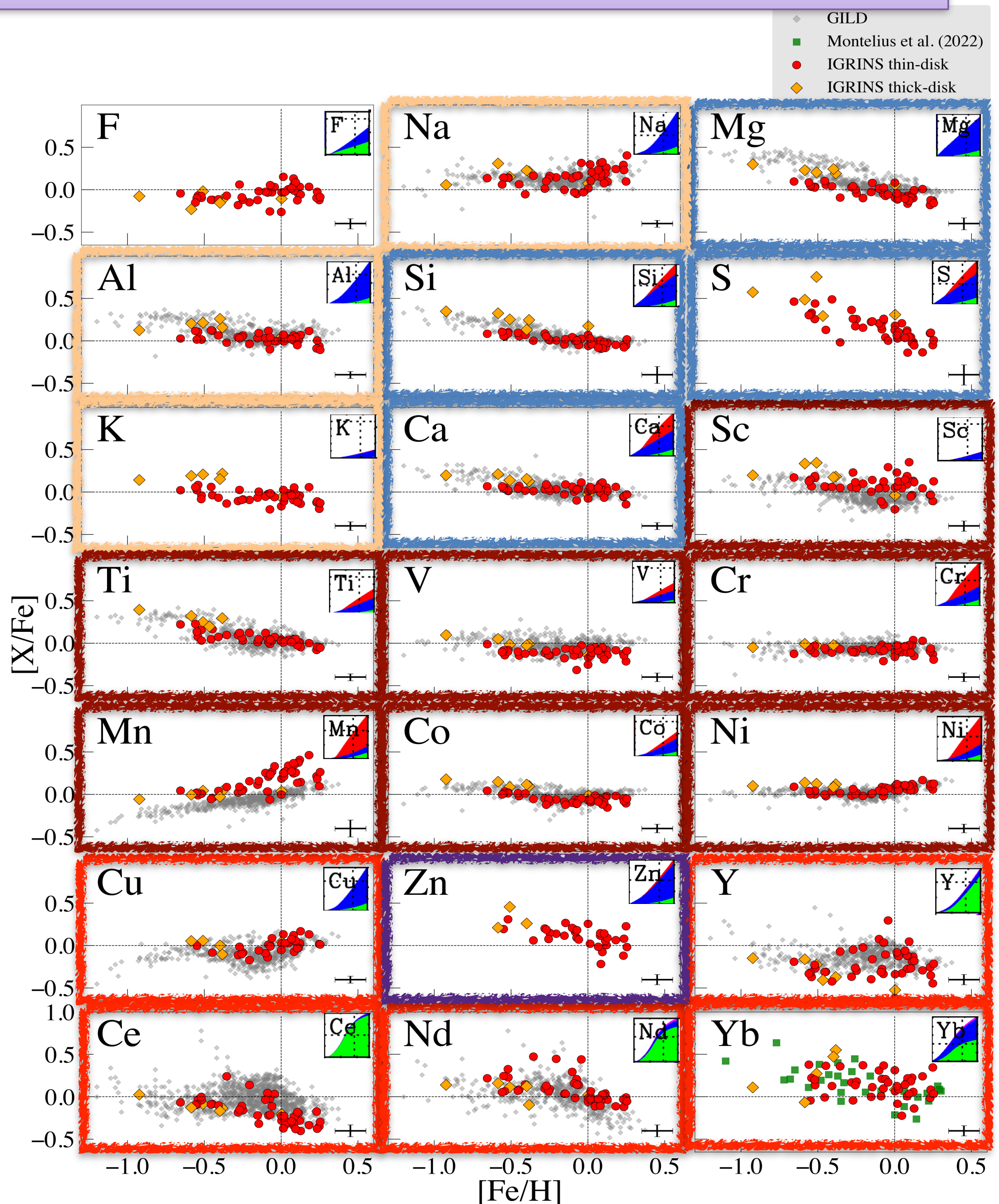

- α elements
- Odd-z elements
- Iron-peak elements
- Between iron-peak and neutron-capture elements
- Neutron-capture elements

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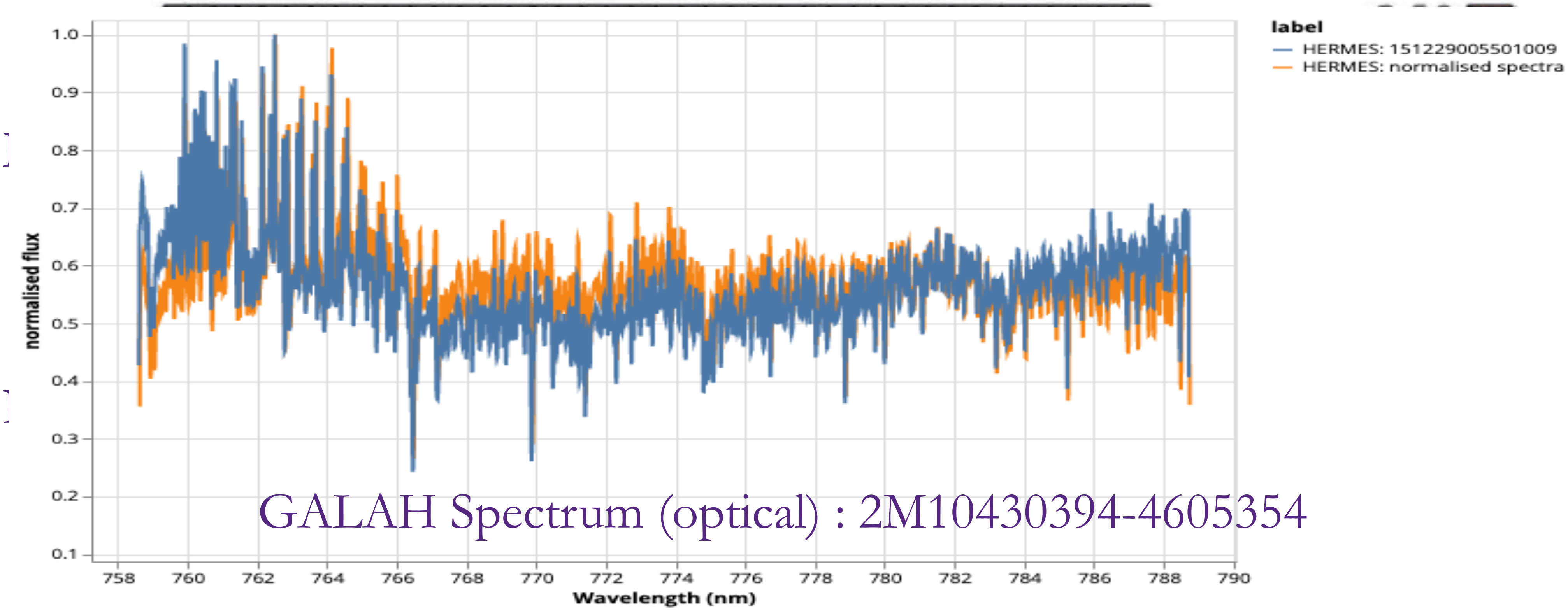
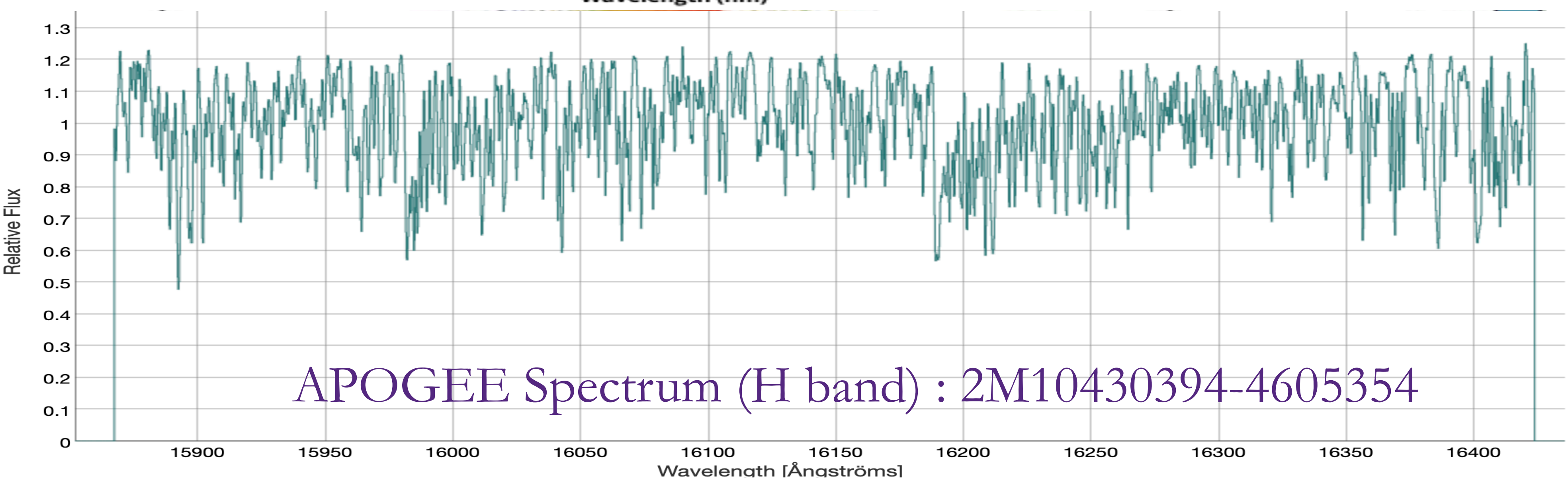
Talk by Nils Ryde

Thank you!

Challenges



GALAH Spectrum (optical) : 2M10430394-4605354



APOGEE Spectrum (H band) : 2M10430394-4605354

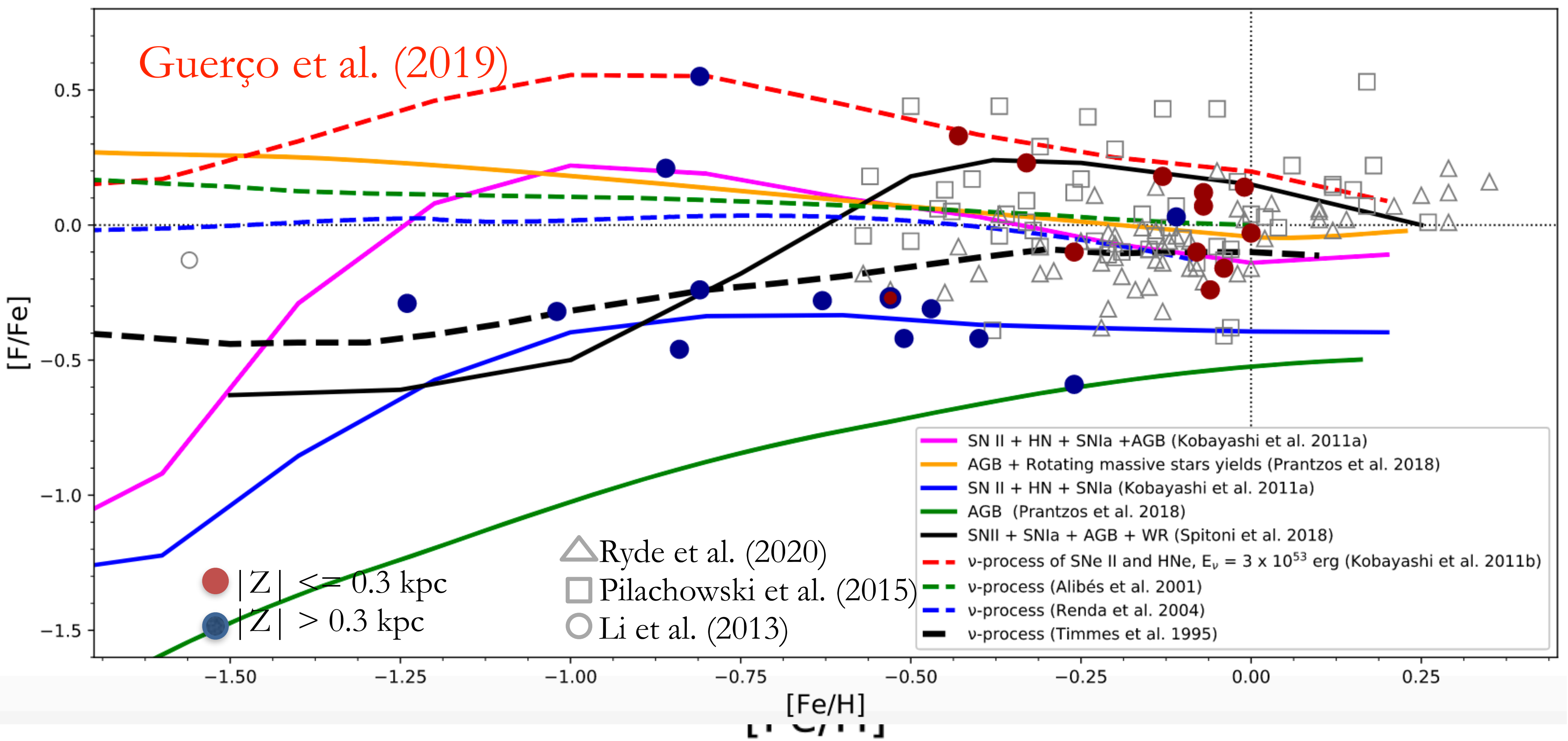
Fluorine

- Origin and/or formation sites under debate
  (Womack et al. (2023), Bijavara-sheshashayana et al. (2024))
  - rapidly rotating massive stars **From ^{14}N via proton and α capture**
  - thermal pulses in asymptotic giant branch stars $^{14}N(n,p)^{14}C(\alpha,\gamma)^{18}O(p,\alpha)^{15}N(\alpha,\gamma)^{19}F$
  - neutrino-process in core collapse supernovae
  - novae $^{17}O(p,\gamma)^{18}F(p,\gamma)^{19}Ne(\beta^{+})F$

- No strong atomic fluorine lines in optical or infrared wavelength regimes, only molecular HF lines in near-IR

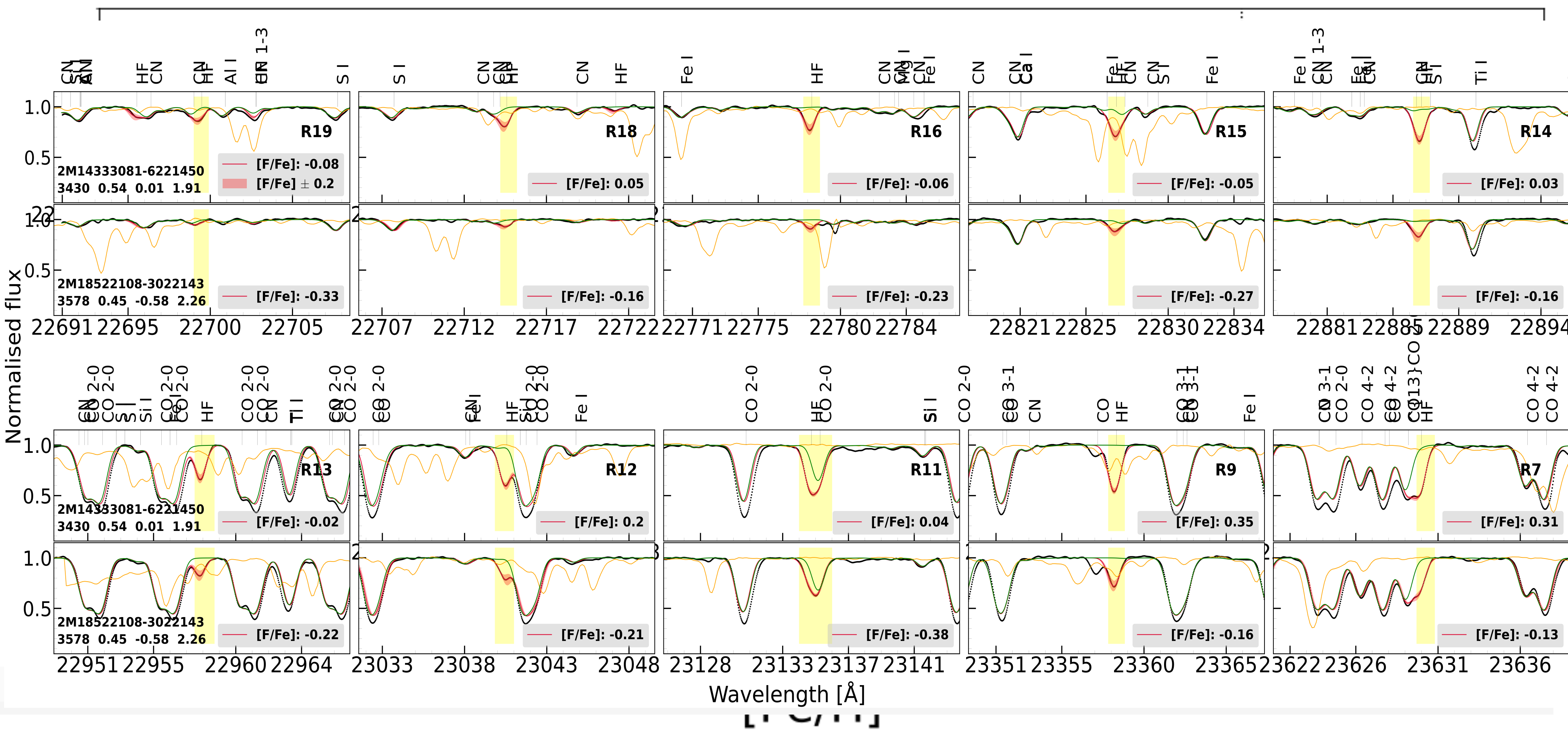
- Most commonly used line : 23358 Å

Fluorine



Nandakumar et al. (2023b)

Fluorine



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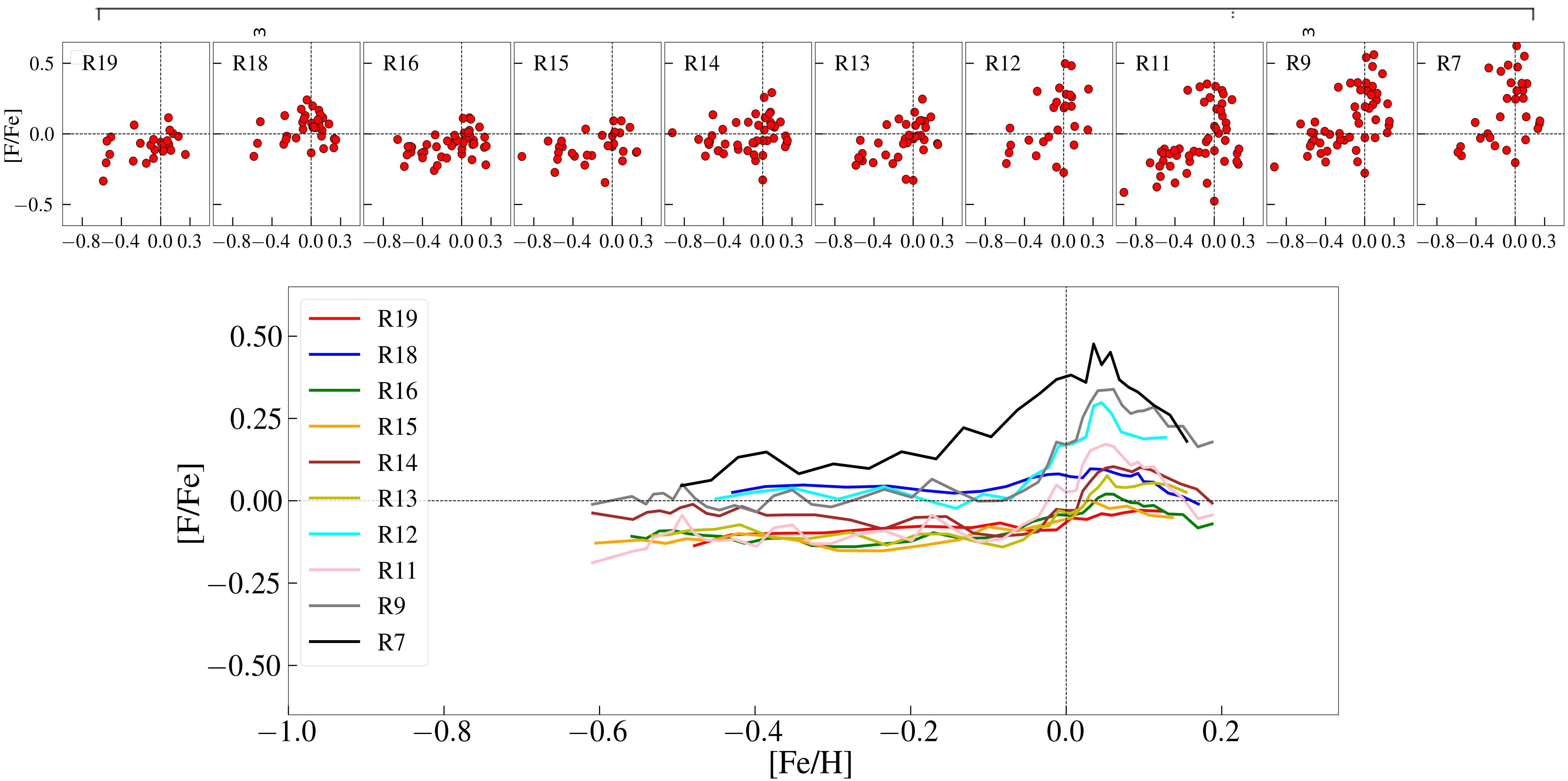

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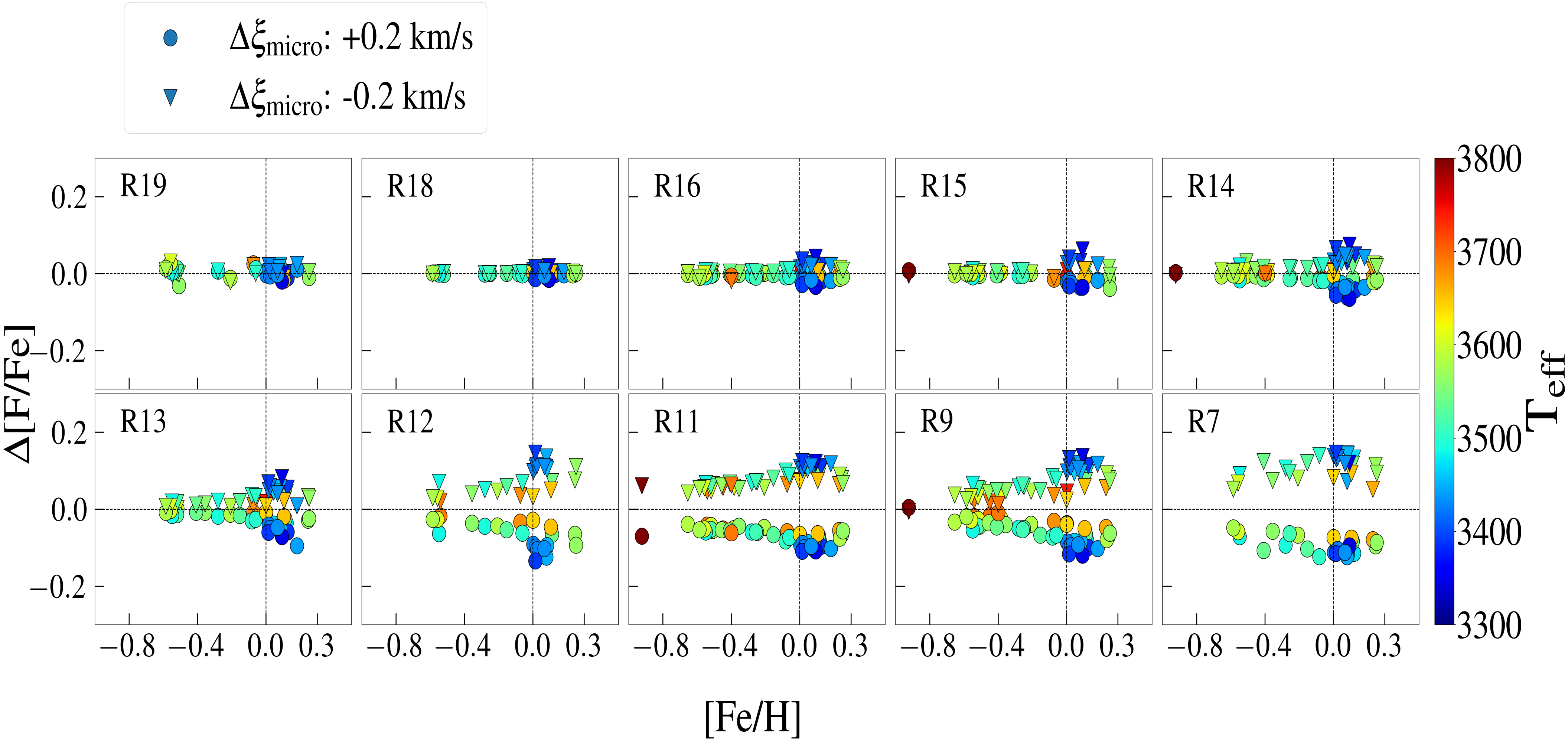

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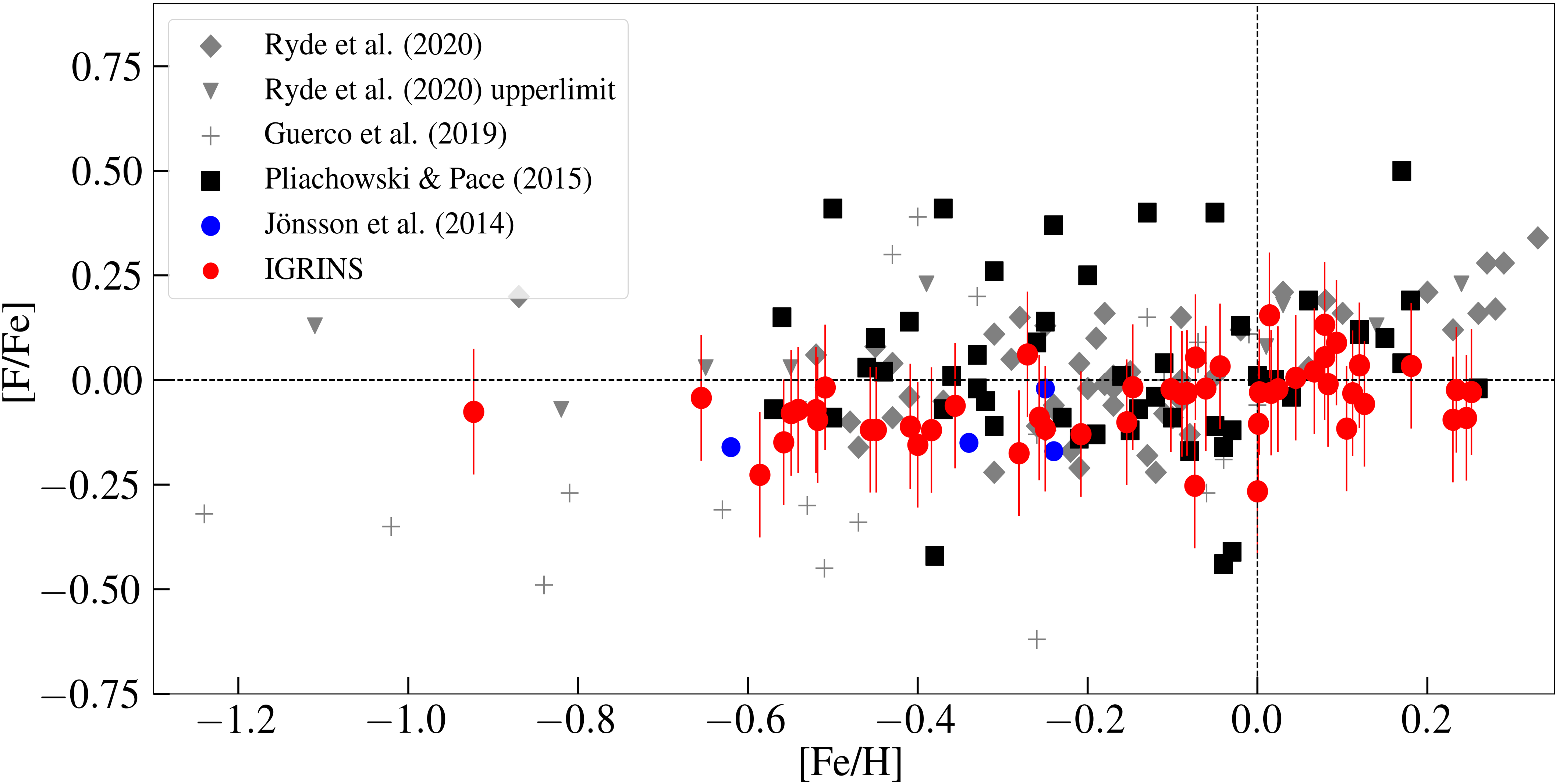

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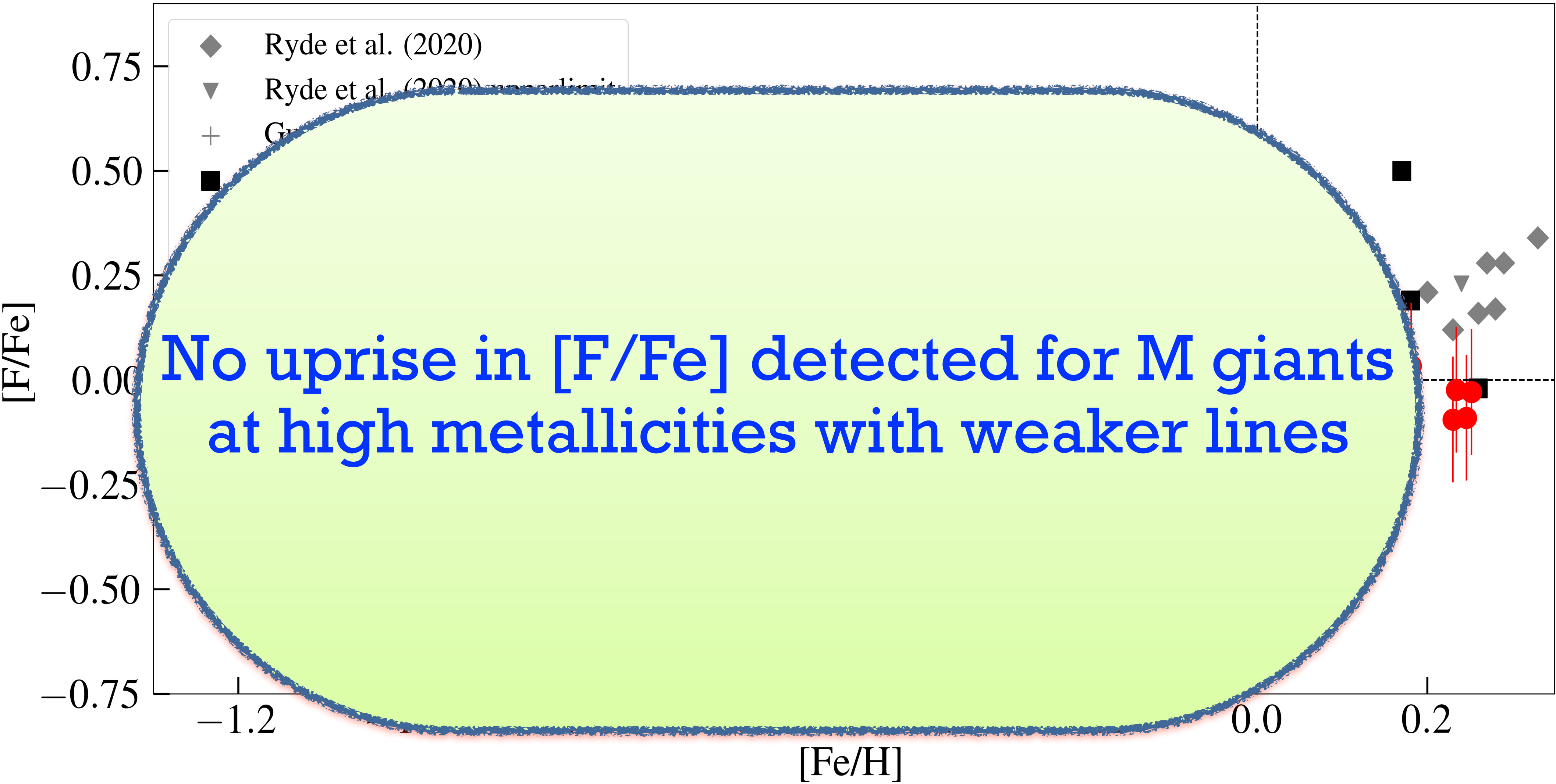


No uprise in [F/Fe] detected for M giants at high metallicities with weaker lines

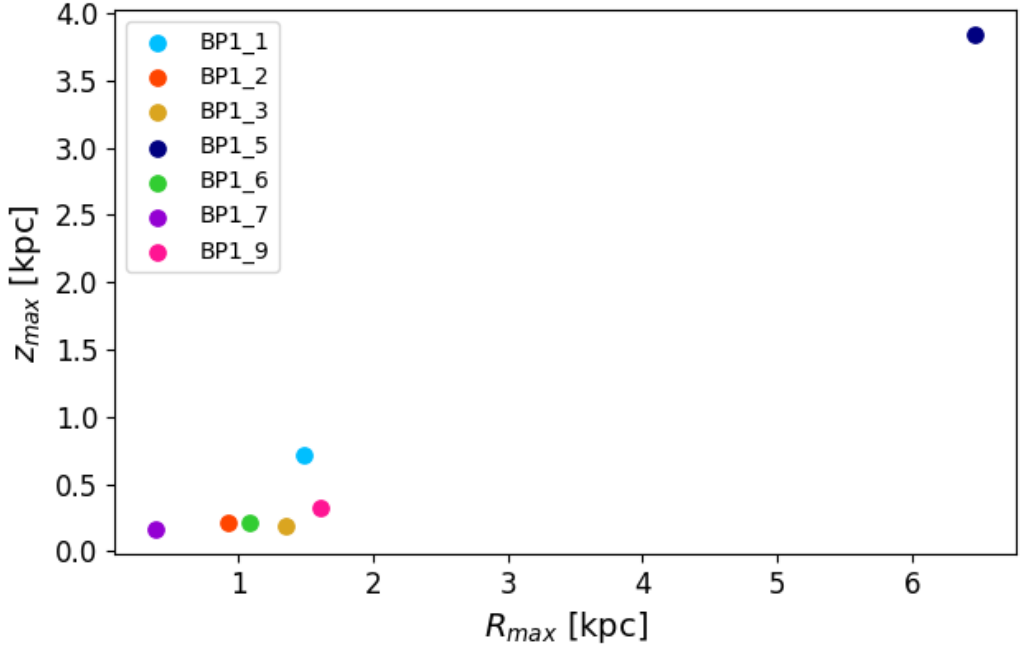
Nandakumar et al. (2023b)

Why study the inner Milky Way

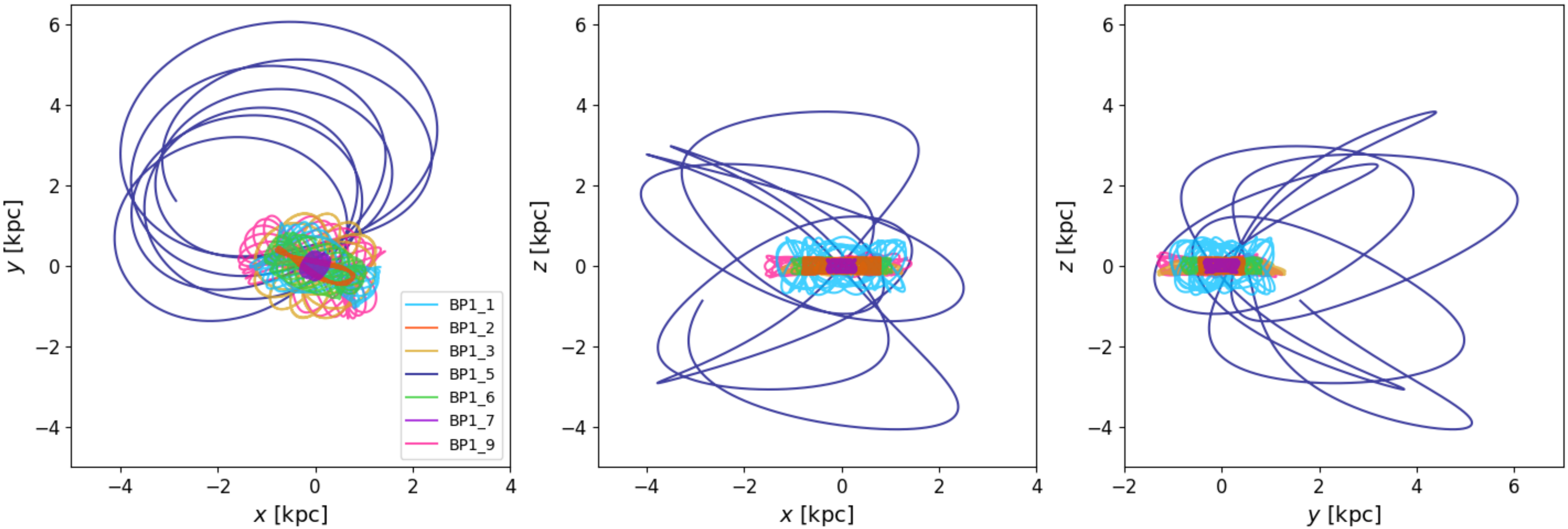
- Unique with an early star formation and chemical enrichment history owing to the inside out formation of the Milky Way.

- Strong magnetic field, dense gas and high turbulence compared to those in the solar neighbourhood (SN).

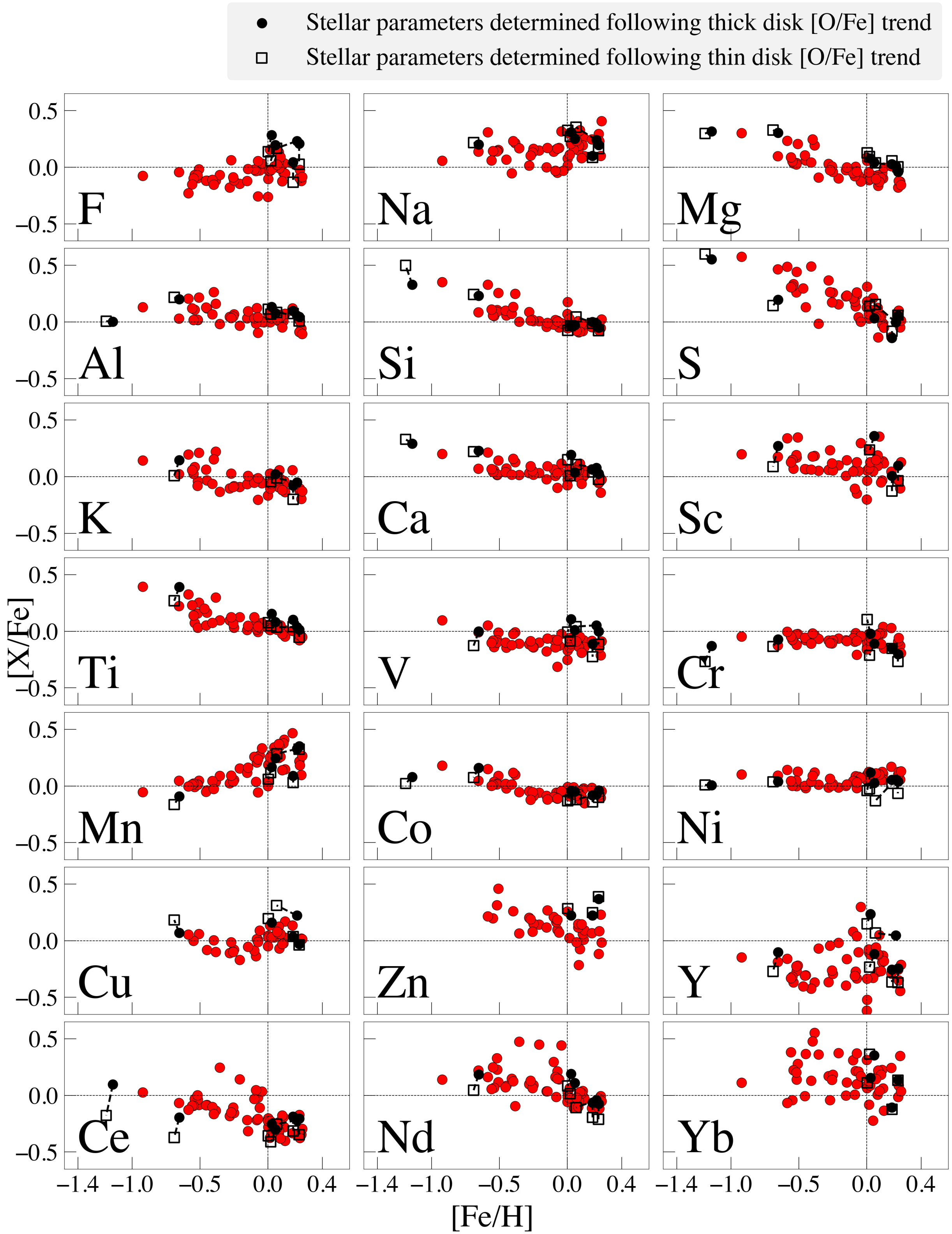
- Ideal proxy for understanding initial stages of typical spiral galaxy formation and evolution.



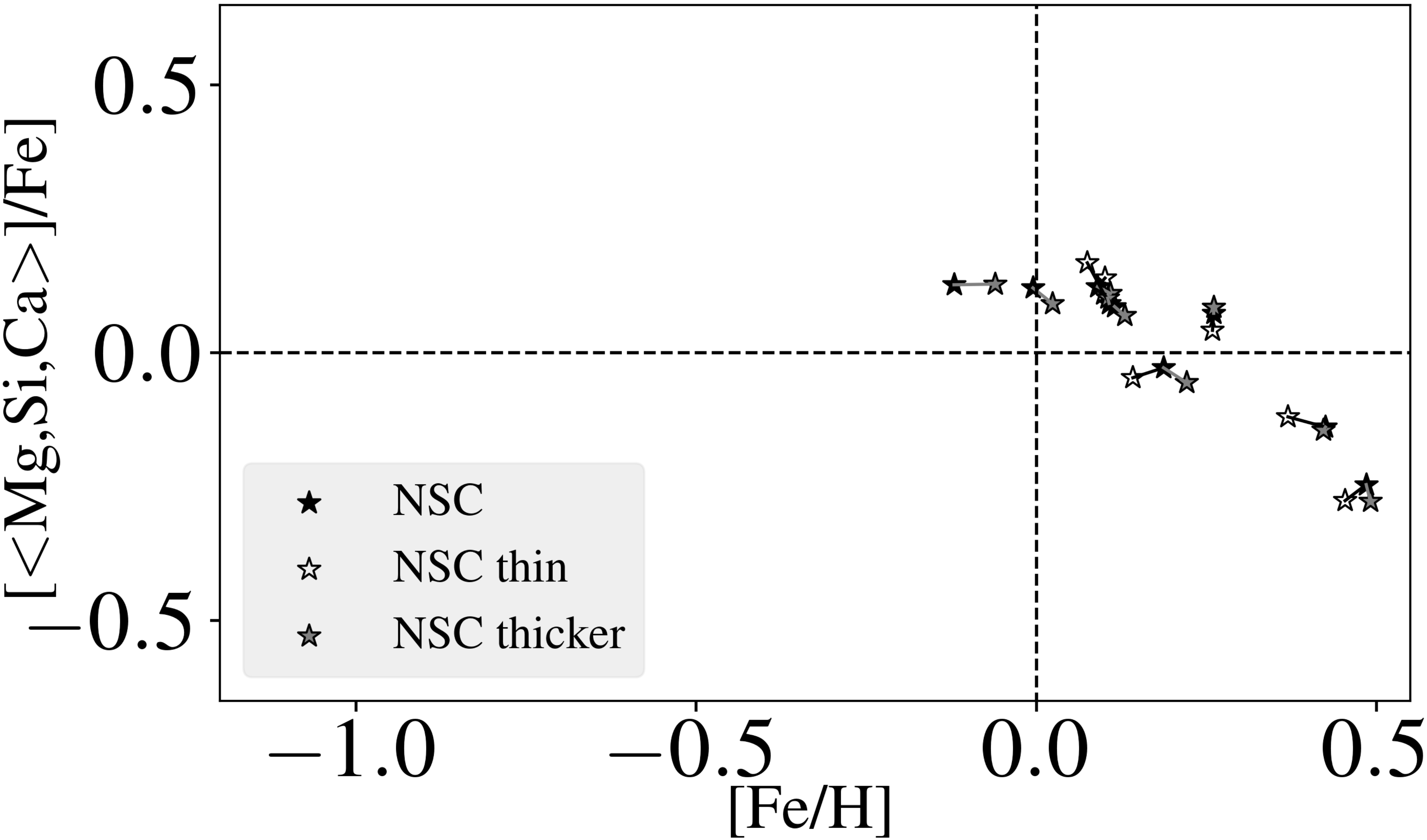
BP1_1
BP1_2
BP1_3
BP1_5
BP1_6
BP1_7
BP1_9
z_{max} [kpc]
R_{max} [kpc]

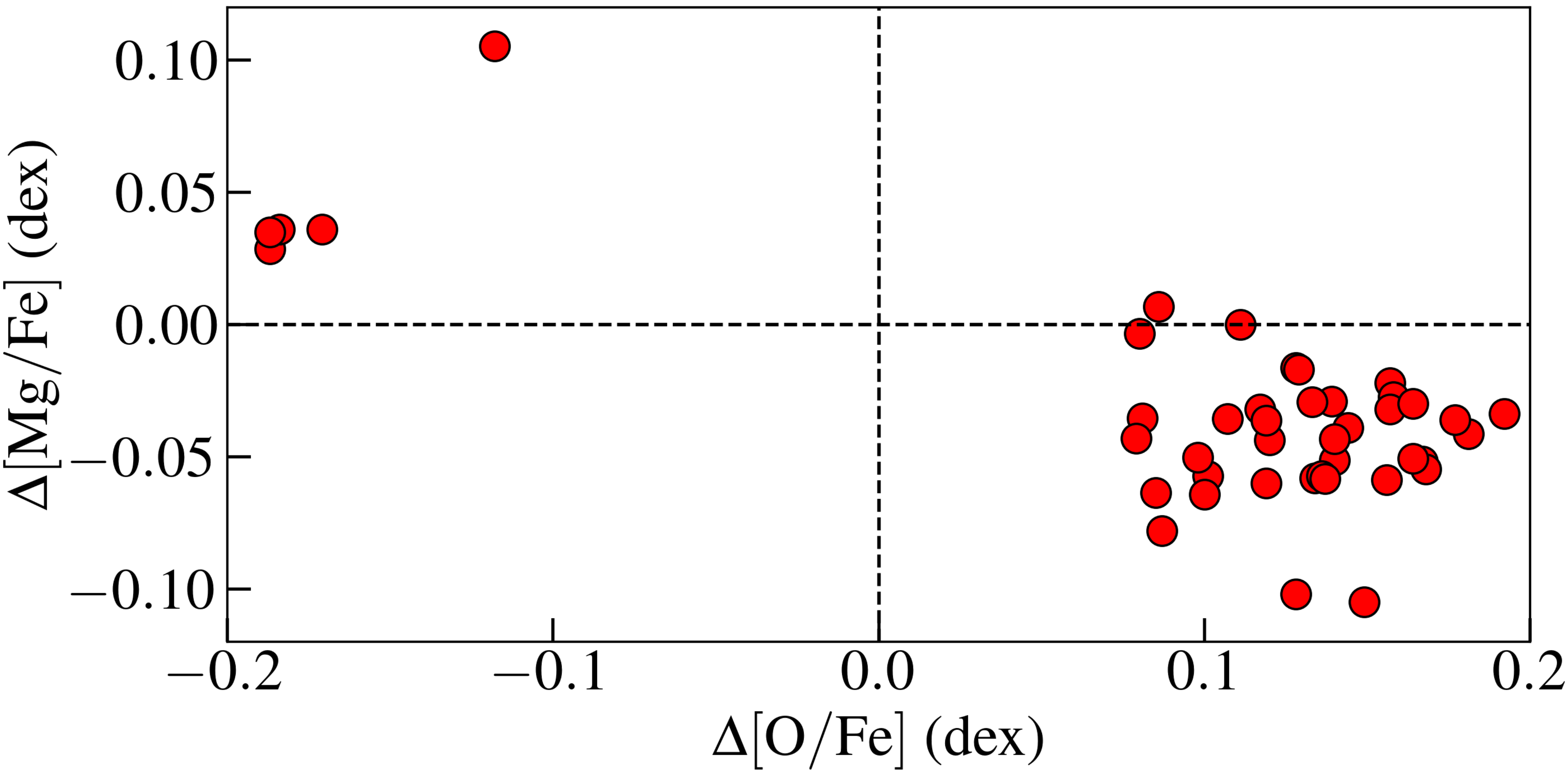


y [kpc]
x [kpc]
BP1_1
BP1_2
BP1_3
BP1_5
BP1_6
BP1_7
BP1_9
z [kpc]
x [kpc]
z [kpc]
y [kpc]



Stellar parameters determined following thick disk [O/Fe] trend
Stellar parameters determined following thin disk [O/Fe] trend
F
Na
Mg
Al
Si
S
K
Ca
Sc
Ti
V
Cr
Mn
Co
Ni
Cu
Zn
Y
Ce
Nd
Yb
[X/Fe]
[Fe/H]


0.5
0.0
−0.5
[<Mg,Si,Ca>]/Fe
NSC
NSC thin
NSC thicker
−1.0
−0.5
0.0
0.5
[Fe/H]



0.10
0.05
0.00
−0.05
−0.10
Δ[Mg/Fe] (dex)
−0.2
−0.1
0.0
0.1
0.2
Δ[O/Fe] (dex)

Stellar parameters

- Effective temperature (Teff), surface gravity (logg), metallicity ([Fe/H]) and microturbulence (χmicro).

- Determination of Teff in M giants :
  - Interferometry (Mozurkewich et al. 2003)
  - Color - Teff relation (Bessel et al. 1998)
  - Infrared flux method (IRFM)(Blackwell & Shallis 1977,Casagrande et al. 2008)

Bright stars

Uncertainties in reddening estimates

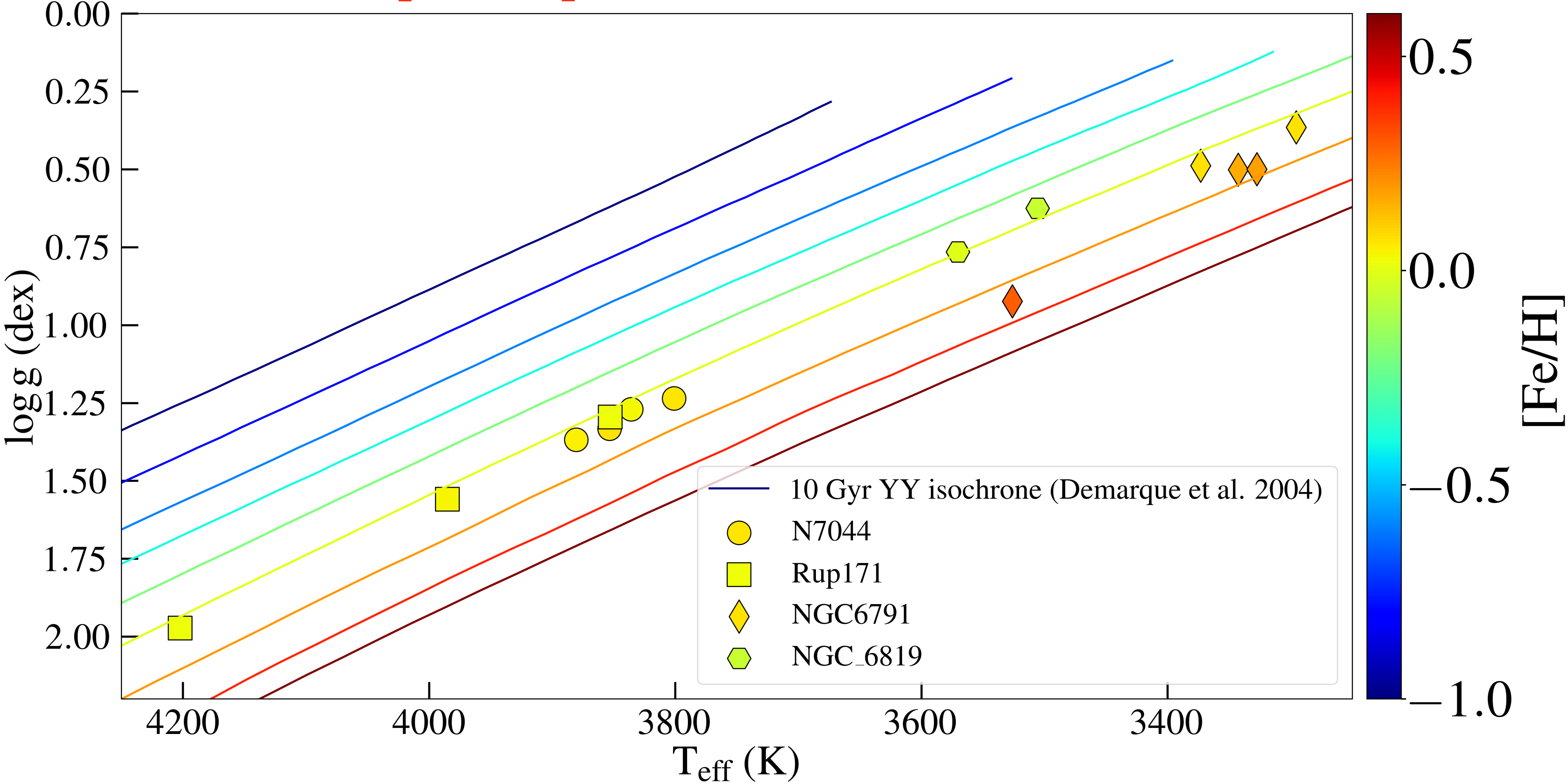
- CO band heads in low-resolution K-band spectra (Schultheis et al. 2016, Nandakumar et al. 2018)
- K band Scandium lines (Thorsbro et al. 2020)

More tests

Further validation: open clusters

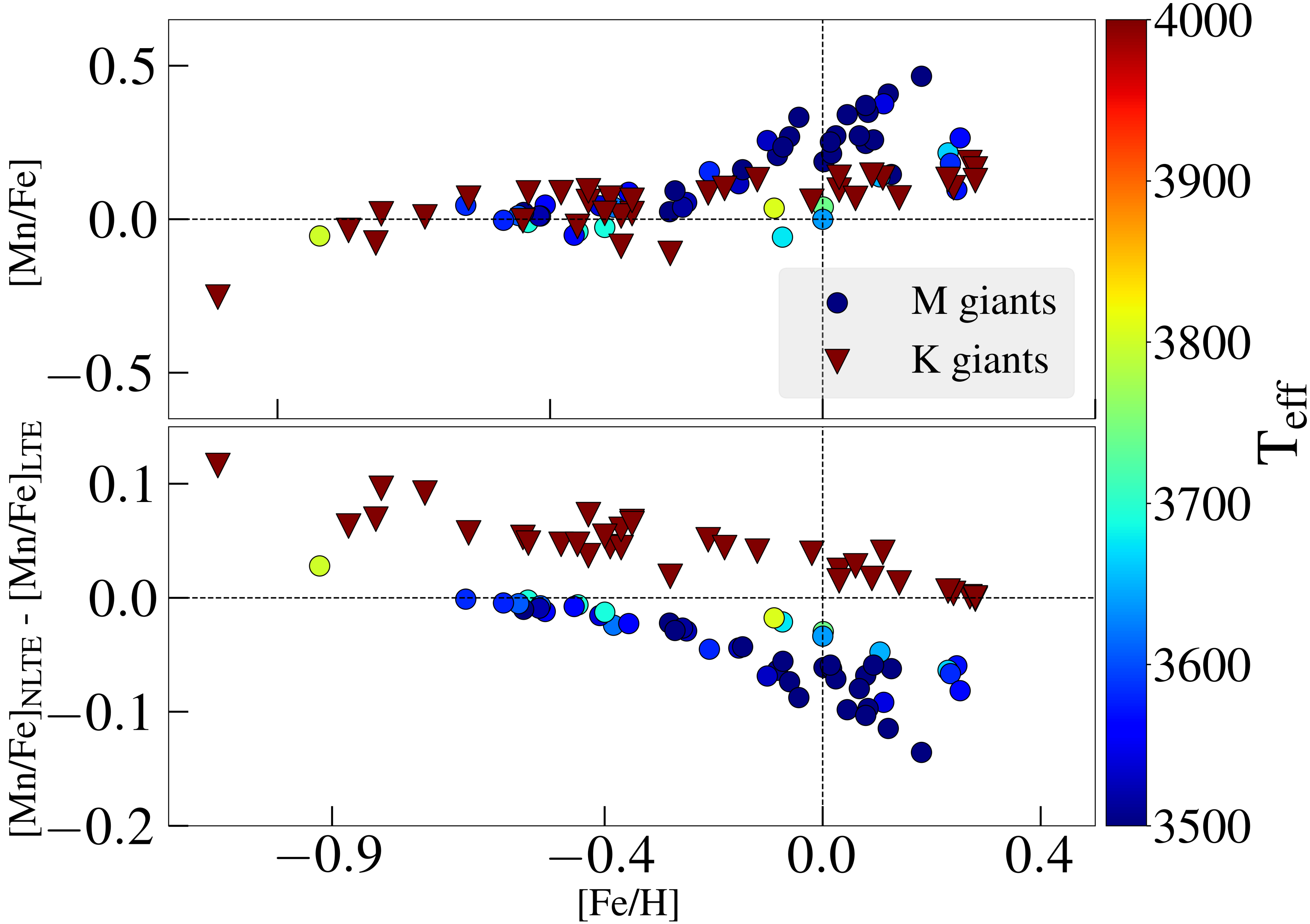
GIANO HK band analysis of open cluster members

Narrow [Fe/H] distribution for OC members!!



Bijavara-Sheshayana et al. (2024)

Manganese



[Mn/Fe]
0.5
0.0
−0.5
M giants
K giants
[Mn/Fe]$_{NLTE}$ - [Mn/Fe]$_{LTE}$
0.1
0.0
−0.1
−0.2
−0.9
−0.4
0.0
0.4
[Fe/H]
4000
3900
3800
3700
3600
3500
T$_{eff}$

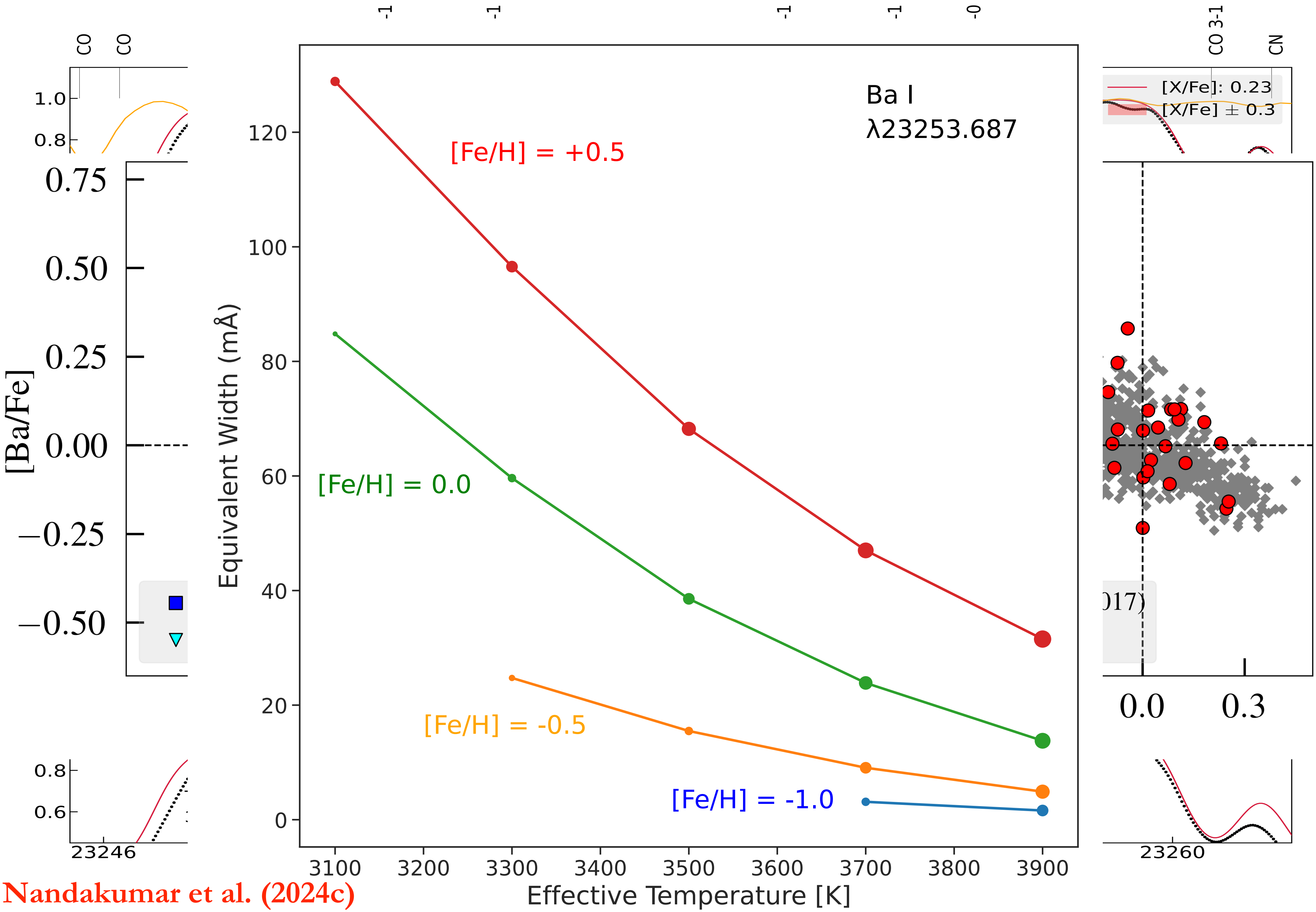
Why study the inner Milky Way?

- Unexplored structures and stellar populations (ability to resolve individual stars)
- Unique with an early star formation and chemical enrichment history owing to the inside out formation of the Milky Way.
- Strong magnetic field, dense gas and high turbulence compared to those in the solar neighbourhood (SN).
- Ideal proxy for understanding initial stages of typical spiral galaxy formation and evolution.

Future works

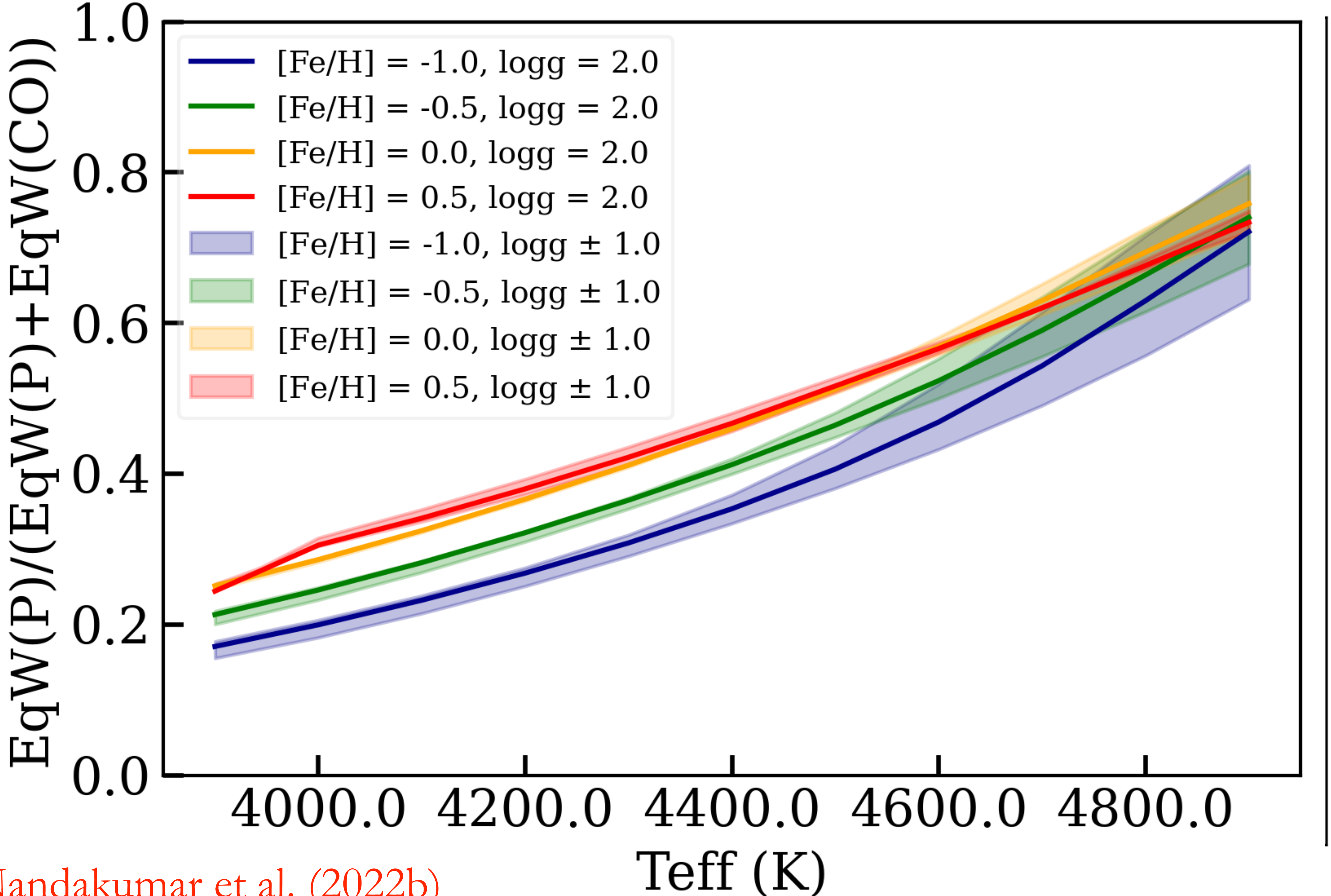
- Analysis of low resolution NIR spectra of nearby M giants (TANSPEC, KMOS etc).
  - Knowledge from high resolution spectroscopic analysis in developing parameter determination methods for low resolution NIR spectra.
  - Machine learning tools to extract information from low resolution spectra
- Near-IR spectroscopic analysis of inner Milky Way clusters (e.g. Lille 1)
- Decipher the connection between gas, stars and dust in the inner Milky Way using multi wavelength data (radio, sub-mm, mid & far IR)
- Models/simulations (chemical evolution, kinematic, cosmological) to decipher the formation and evolution scenarios of inner Milky Way structures
- Future surveys and observing facilities
  - **MOONS** near-infrared survey in H-band, lower resolution (than IGRINS).
  - **Thirty Meter Telescope -** IRIS,MODHIS etc
  - India's 10-m class **national large optical-IR telescope (NLOT)**

Barium



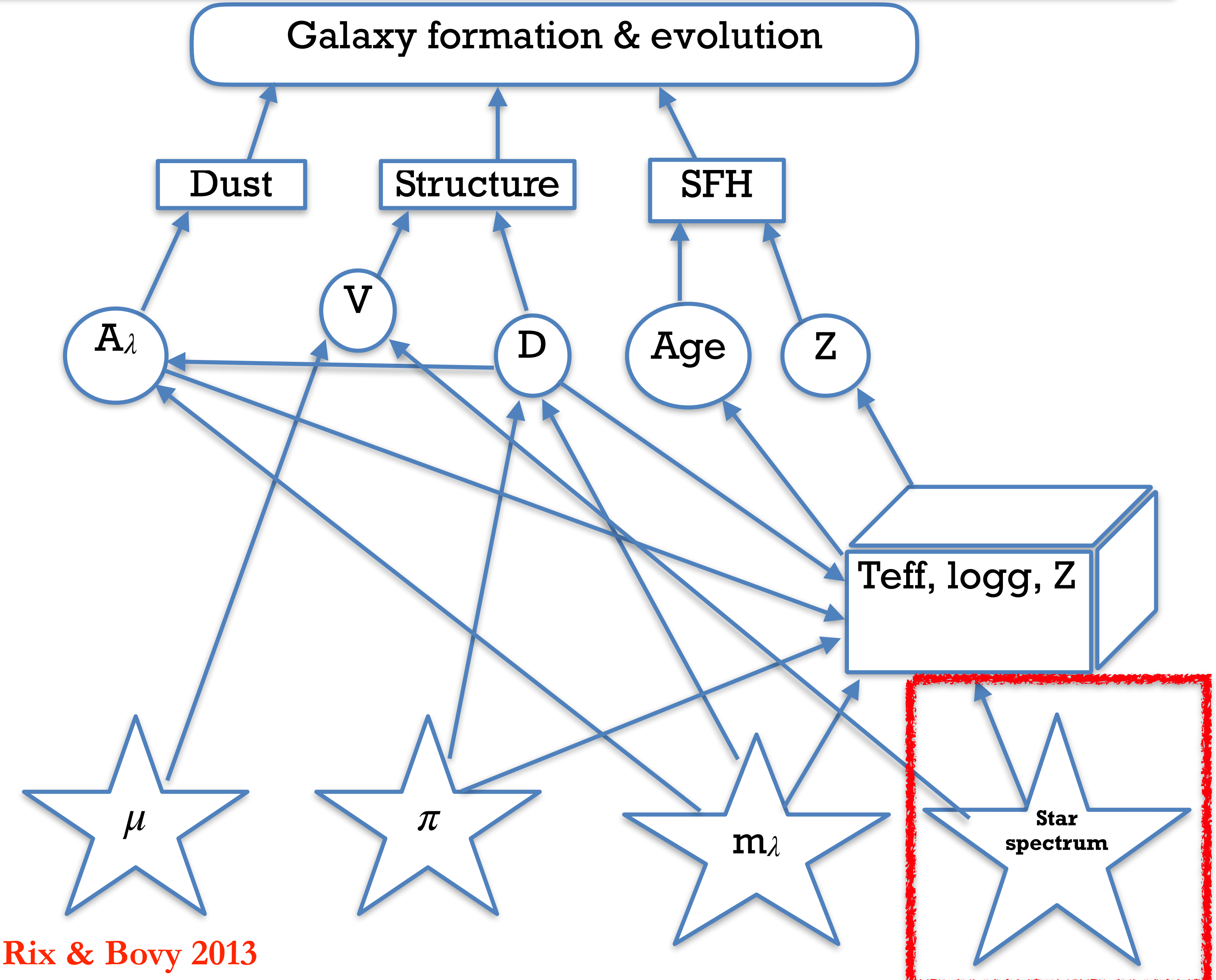
Nandakumar et al. (2024c)

Phosphorus



Nandakumar et al. (2022b)

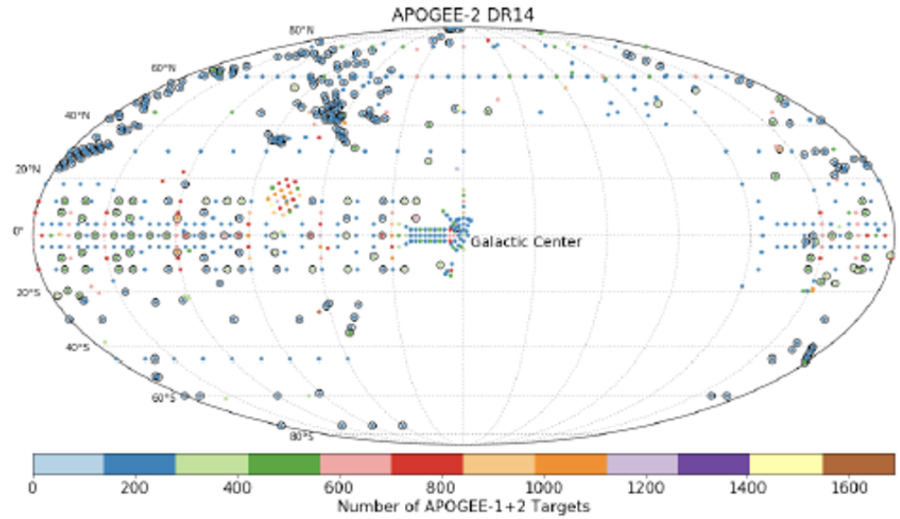
Galactic archaeology: observational perspective



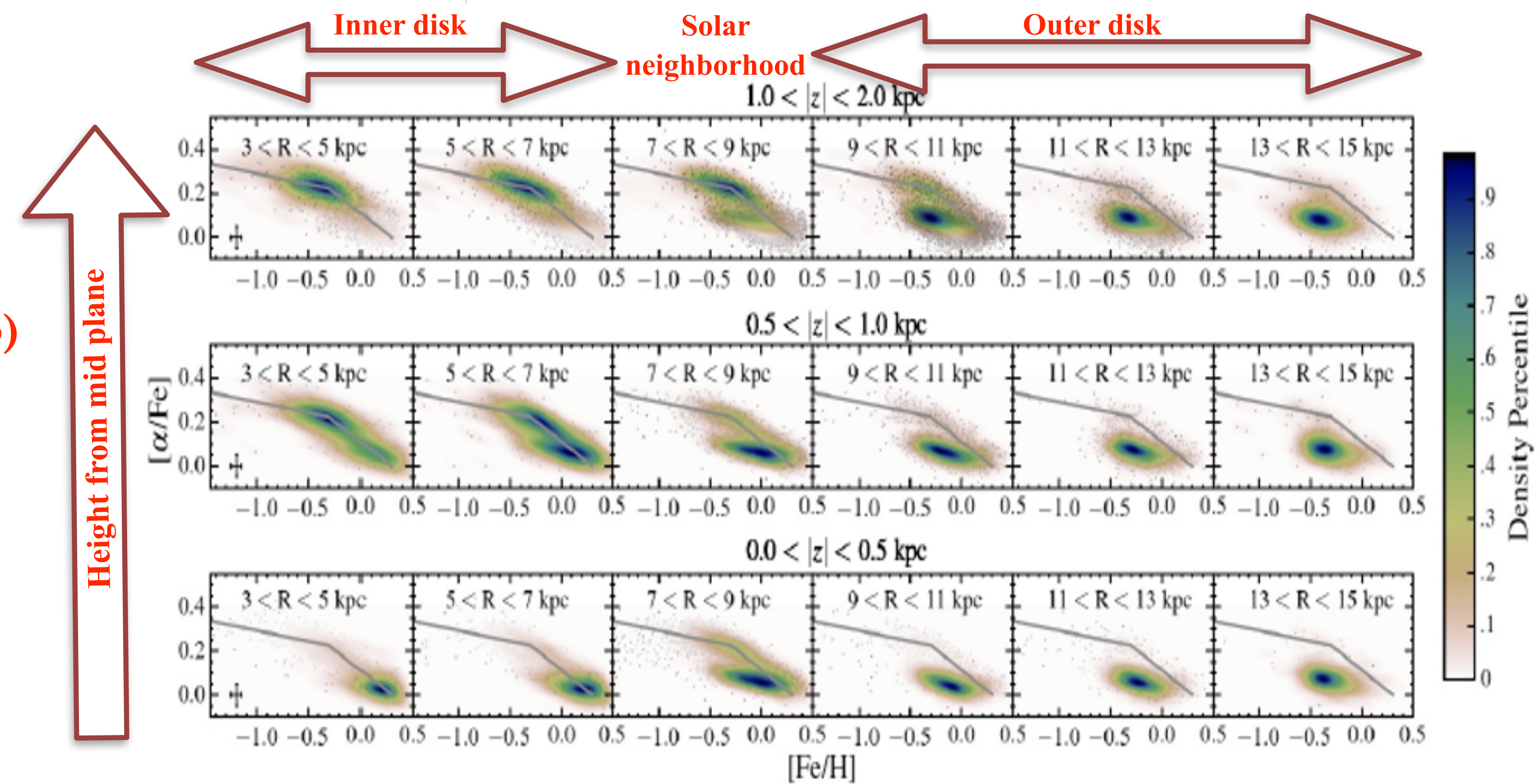
Inspired from Rix & Bovy 2013

Milky Way components

APOGEE

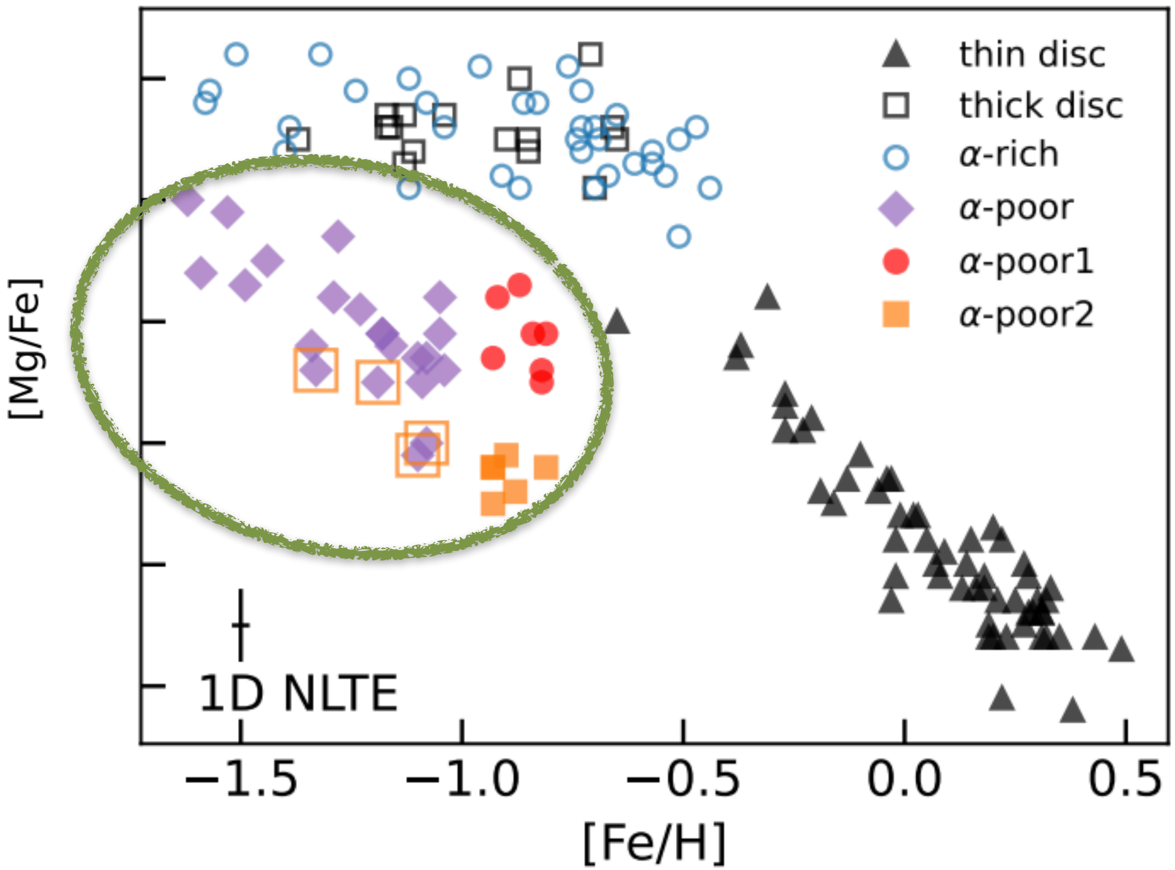


Hayden et al. (2015)



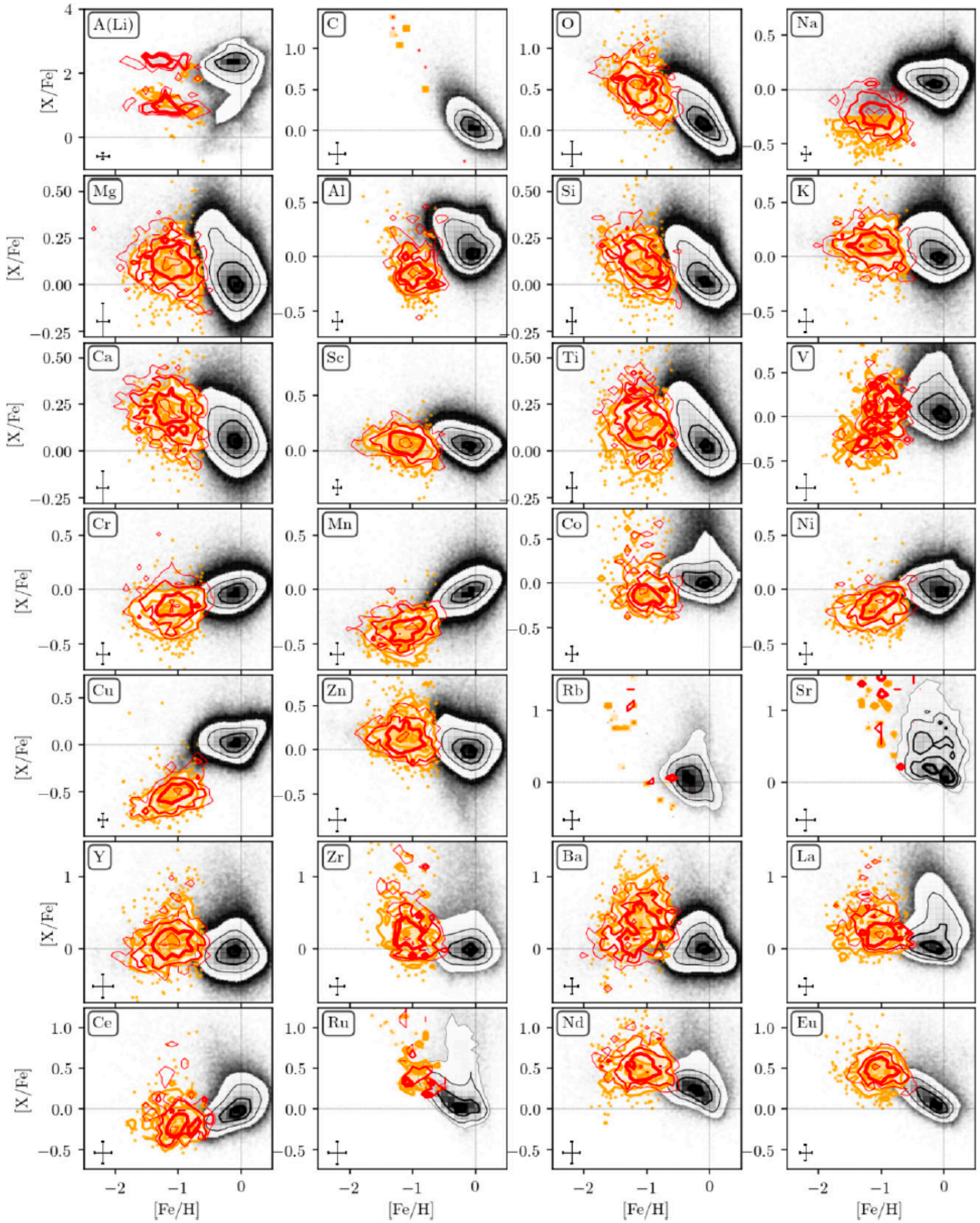
Abundance trends

Accreted stellar population



Nissen & Schuster 2010, Matsuno et al. (2024)

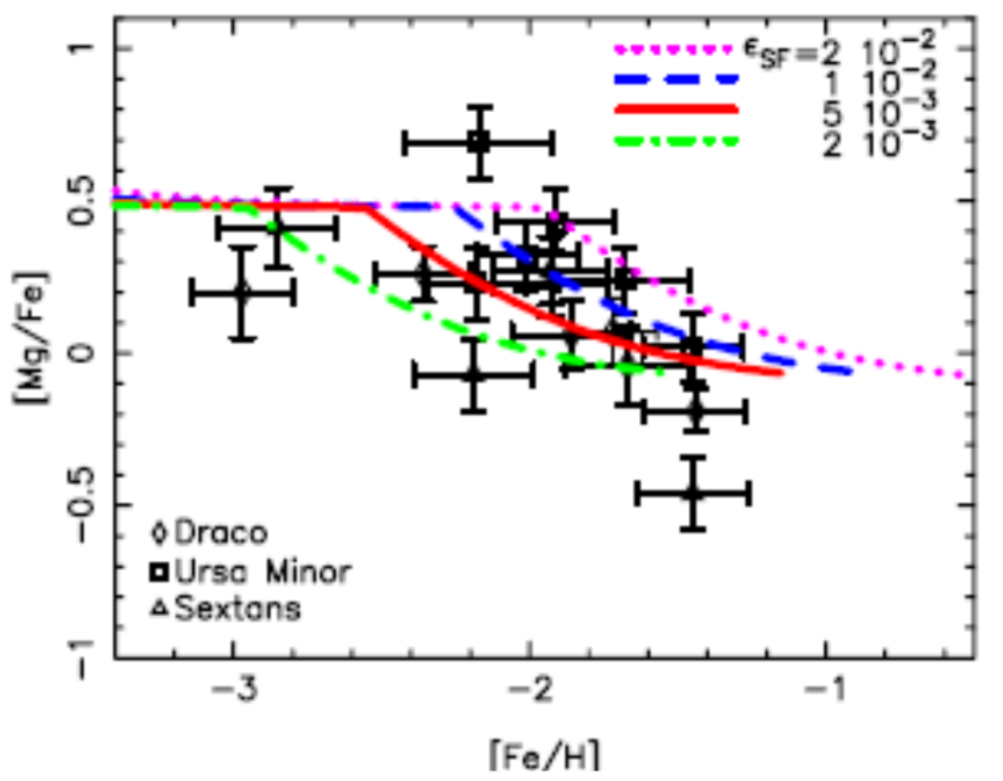
Chemical enrichment



Buder et al (2022)

Abundance trends: SFR & IMF

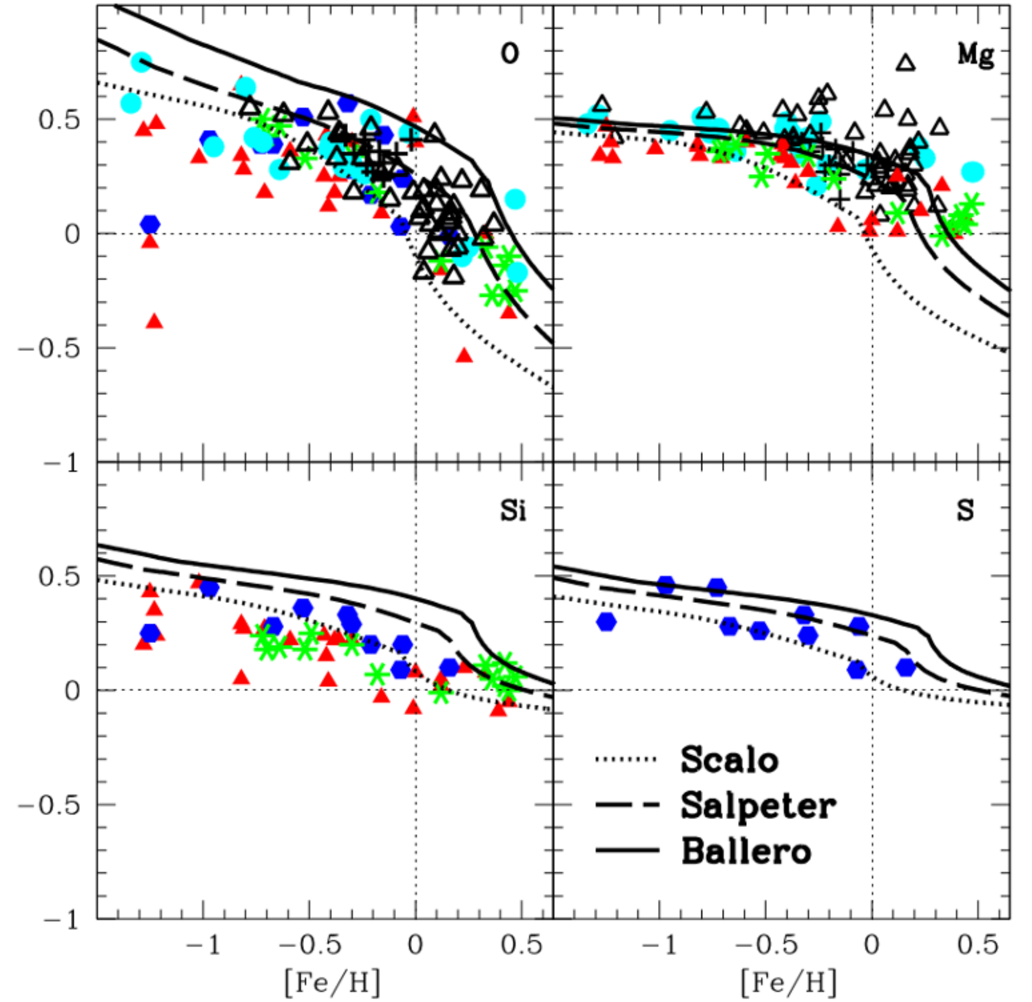
Observations : Shetrone et al. (2001)



Ikuta & Arimoto 2002

Bulge observations

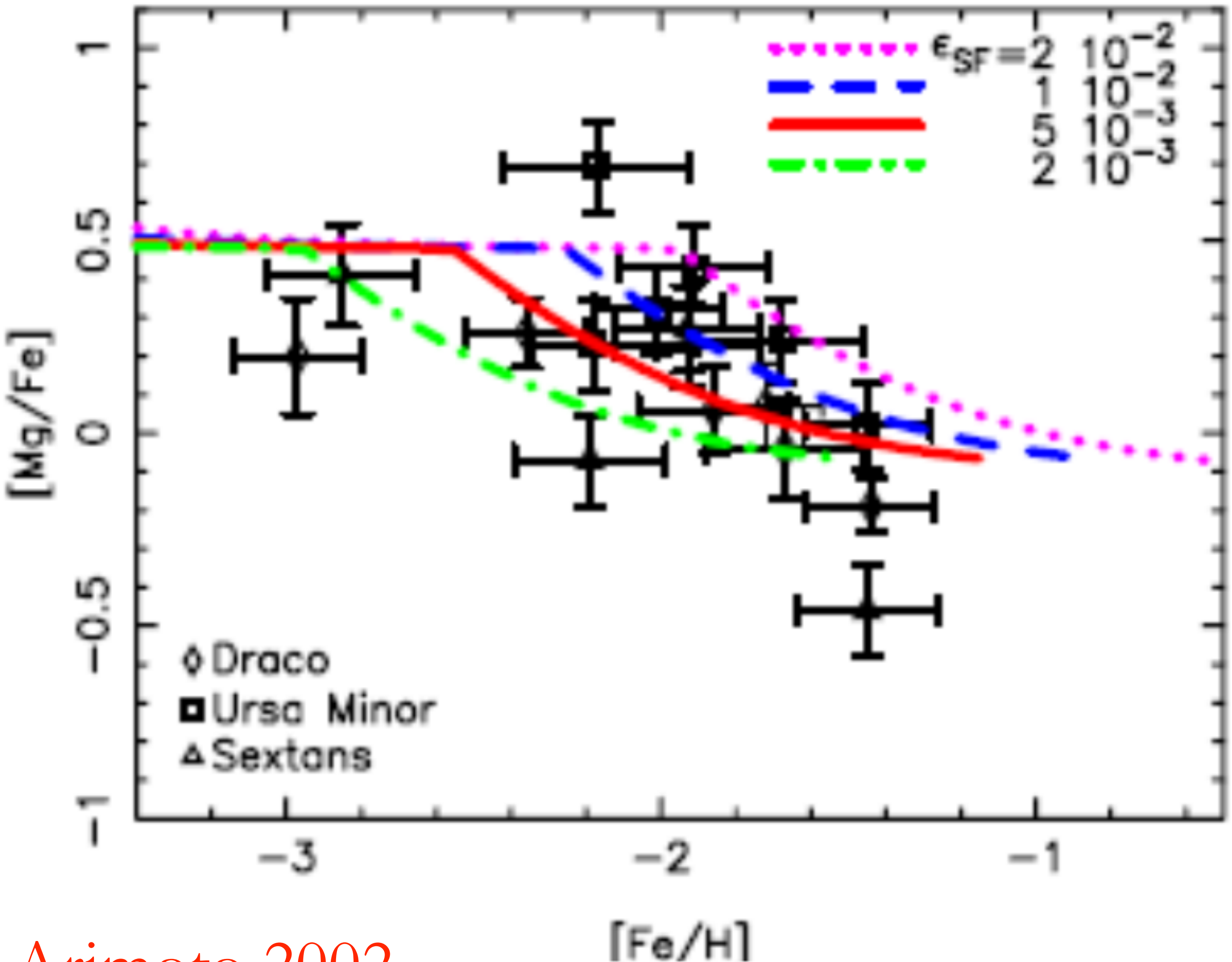
Filled triangles:Alves-Brito et al. (2010)
Plus signs: infrared results from Rich & Origlia (2005)
Filled hexagons: infrared results by Ryde et al. (2009)
Stars: results for microlensed dwarf stars by Bensby et al. (2010)



Cescutti & Matteucci 2011

Abundance trends

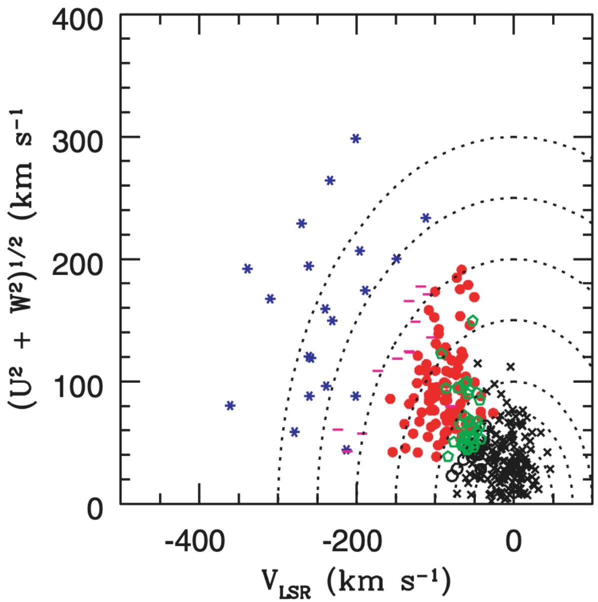
Observations : Shetrone et al. (2001)



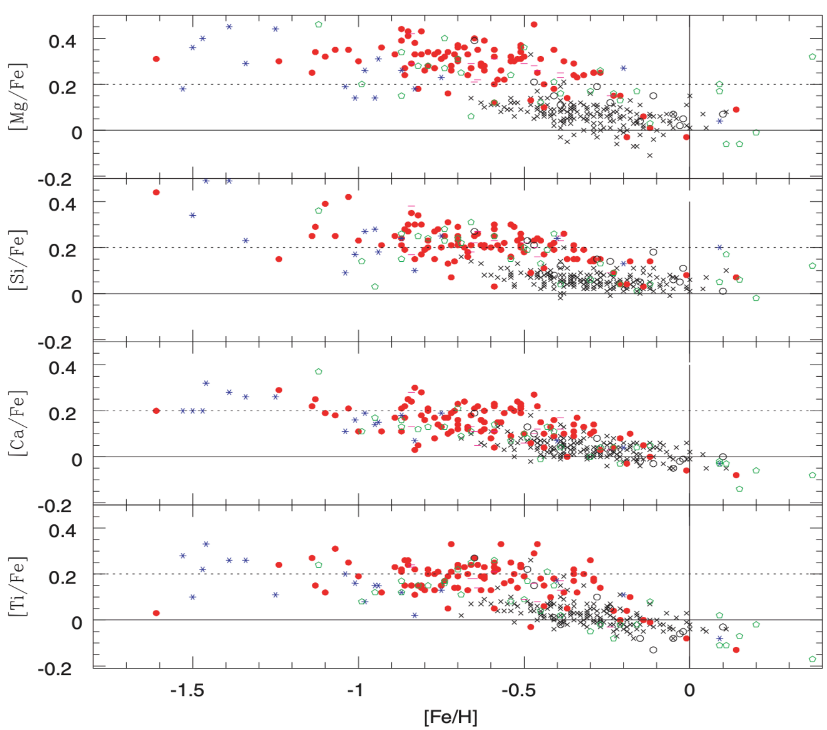
Ikuta & Arimoto 2002

Milky Way components

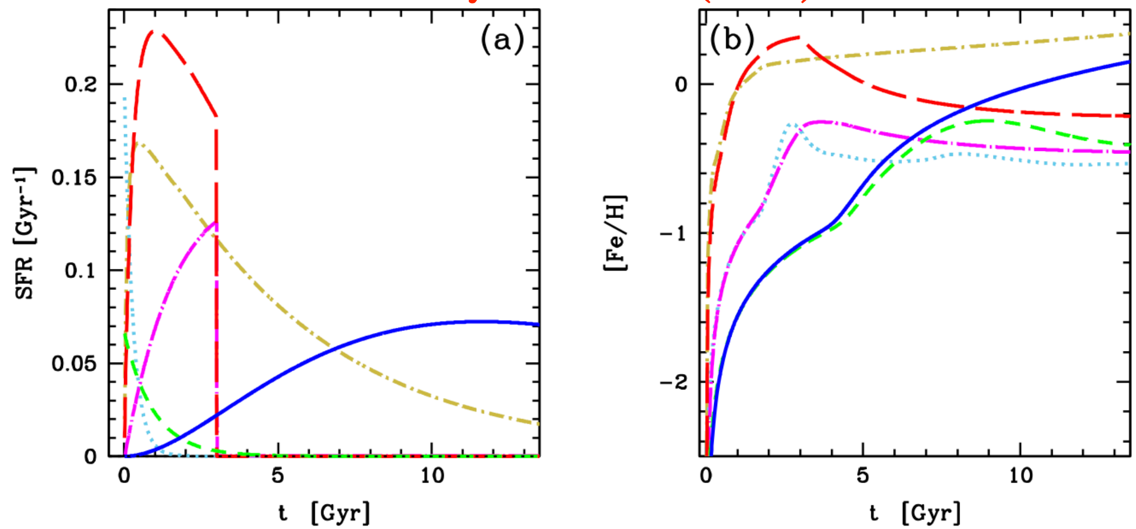
Reddy et al. (2006)

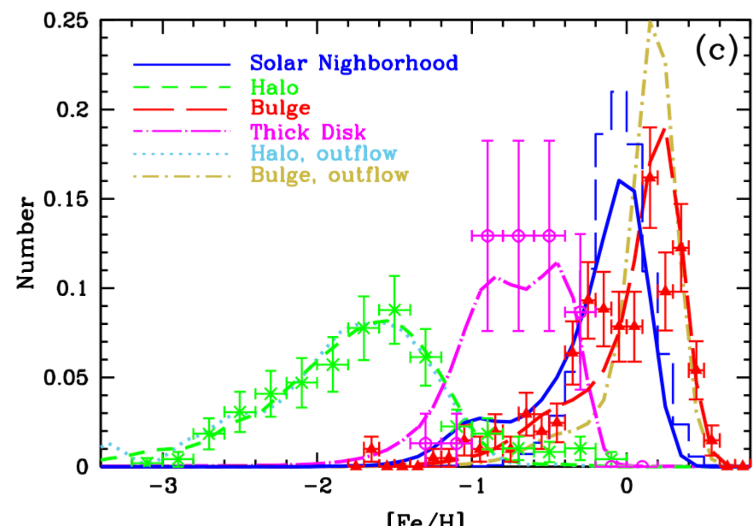


thick-disc, thin-disc, halo, equal probabilities between thin and thick, between thick and halo



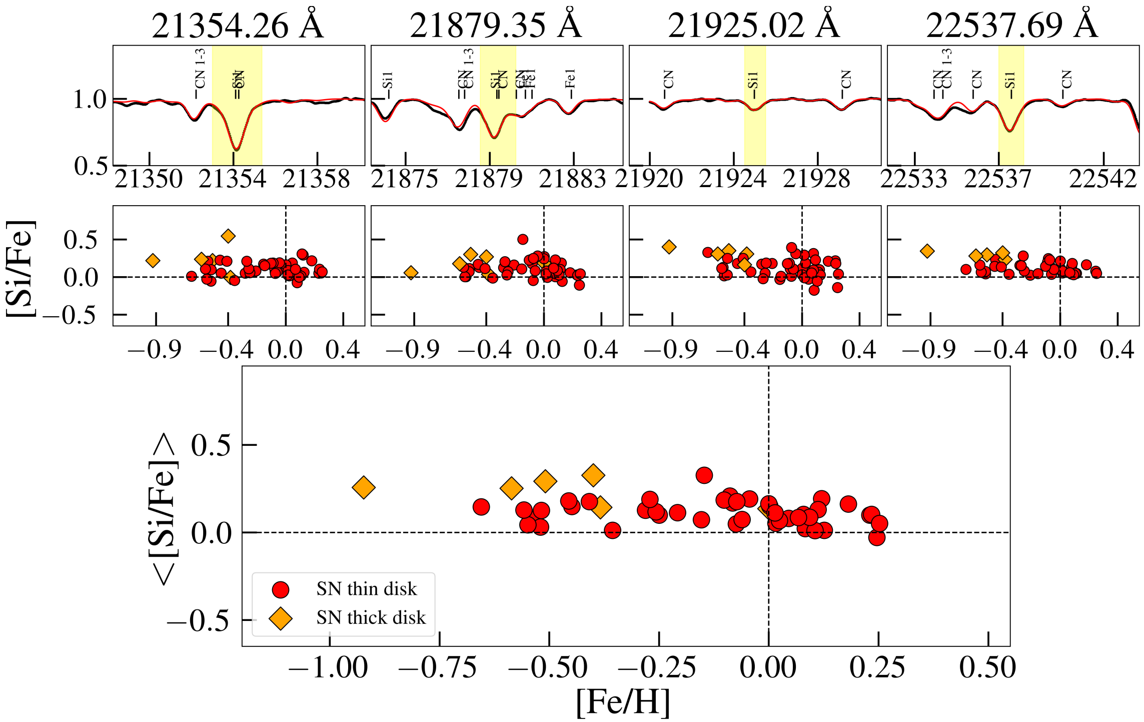
Kobayashi et al. (2020)

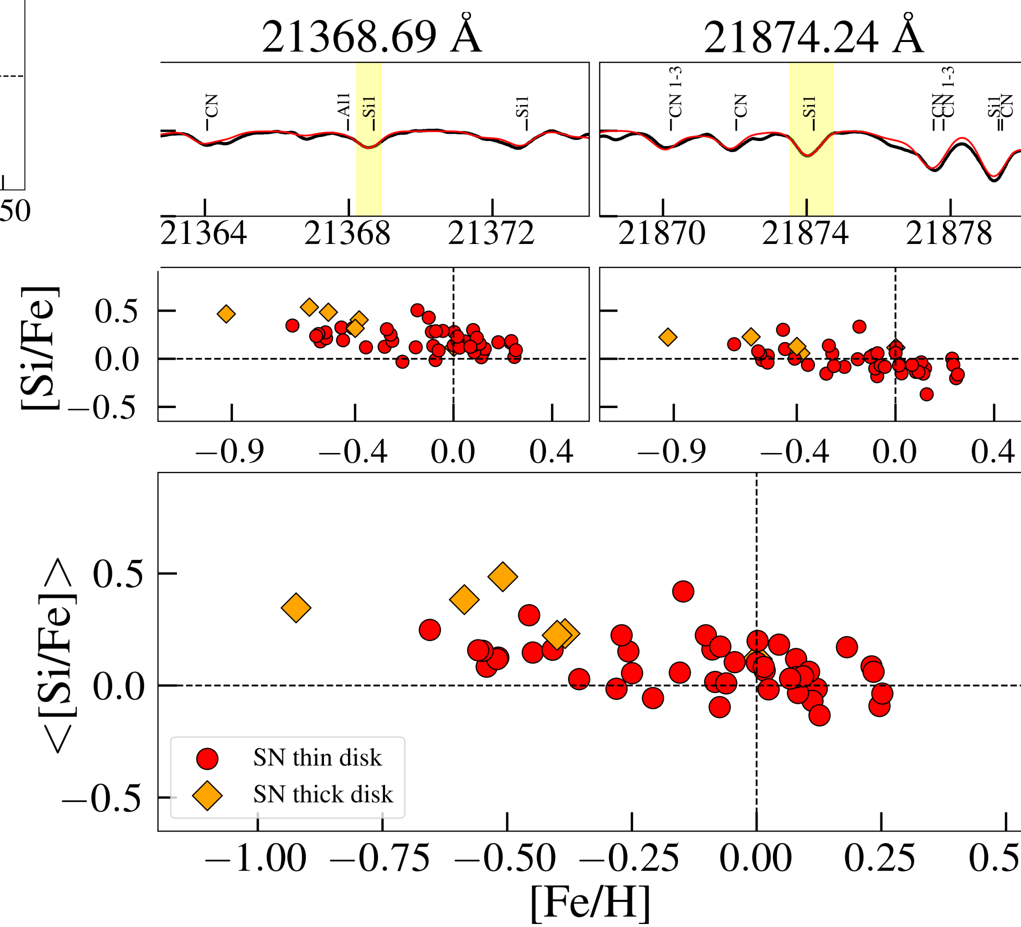




Histogram: Casagrande et al. (2011); Crosses, Chiba & Yoshii (1998); Filled triangles, Zoccali et al. (2008); and open circles, Wyse & Gilmore (1995)

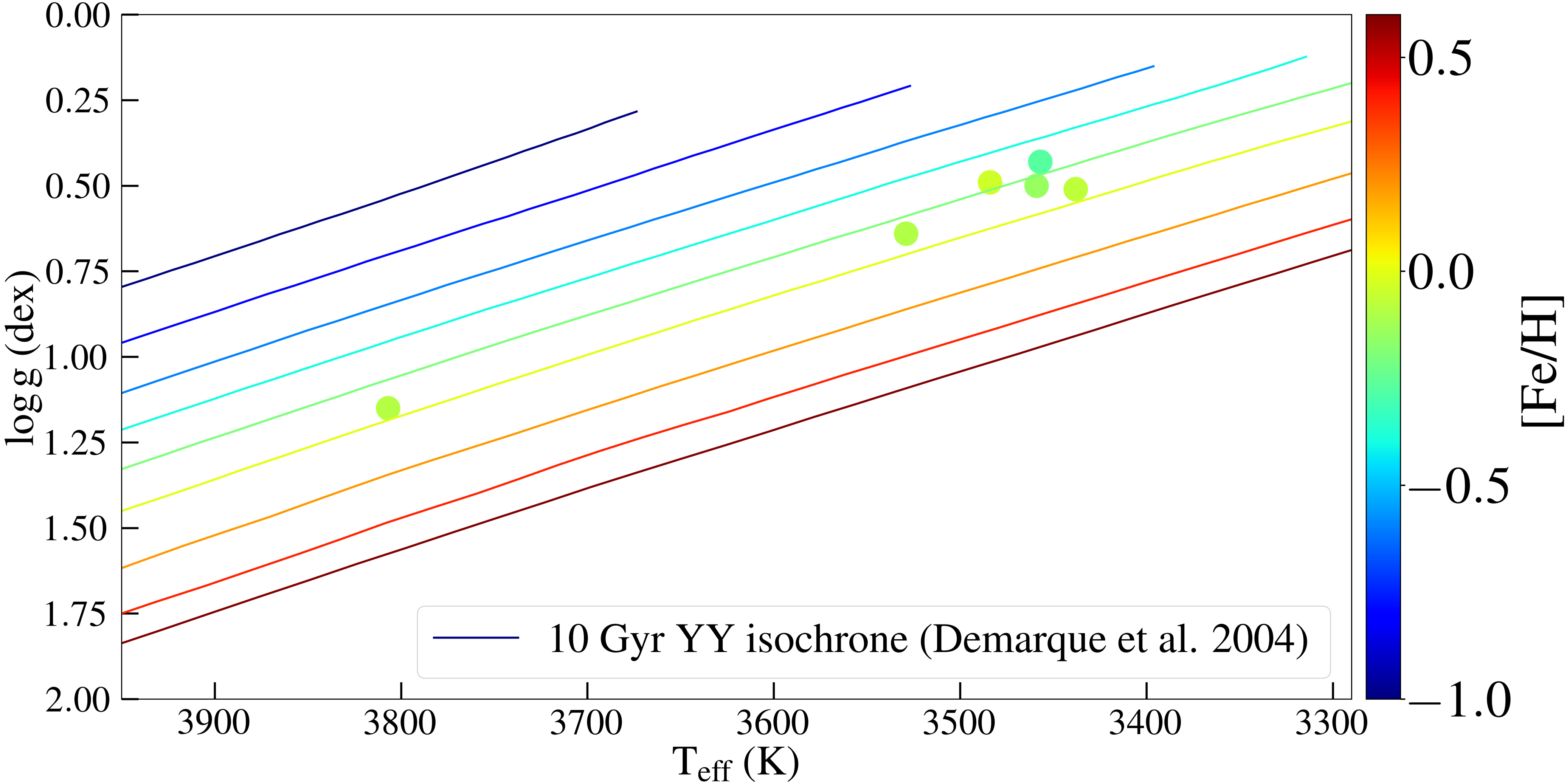
Si lines investigation





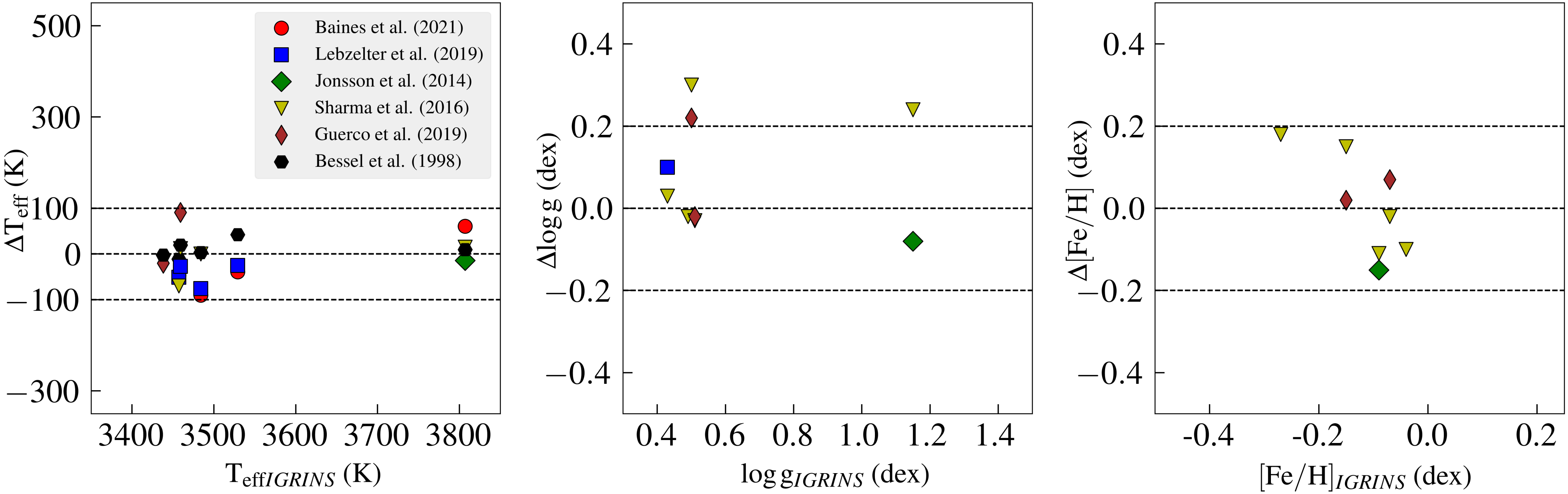
Test: Nearby M giants

- Identified 6 nearby M giants with IGRINS spectra available in IGRINS



- Teff, logg and [Fe/H] from MILES (Sharma et al. 2016)

Test: Nearby M giants



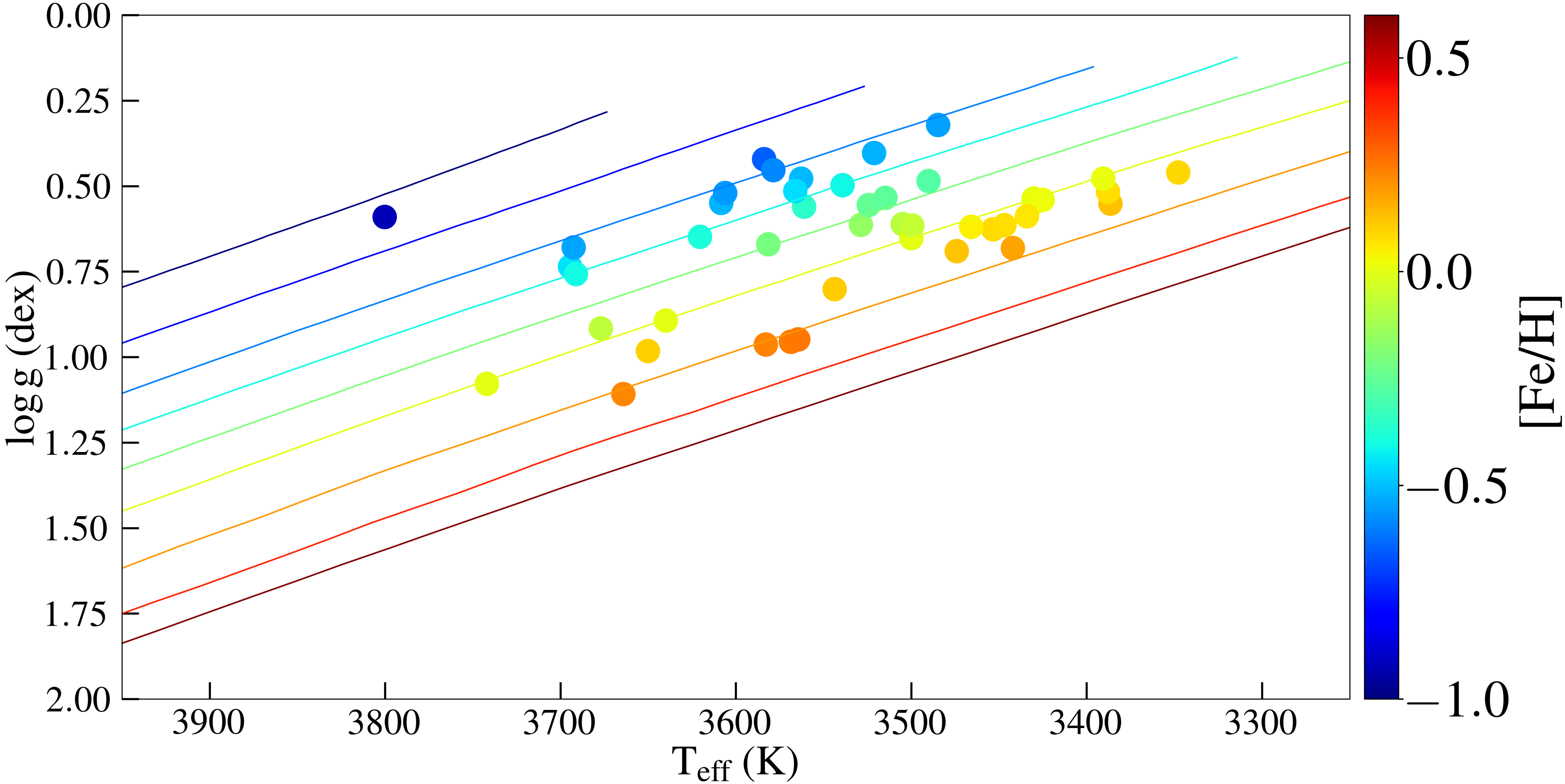
Y axis : Literature - Our method

- Teff-(V-K)0 relation of Bessel et al. 1998

$$T_{\rm eff} = 9102.523 - 3030.654(V-K)_0 + 633.3732(V-K)_0^2 - 60.73879(V-K)_0^3 + 2.135847(V-K)_0^4$$

Catalog: Solar neighbourhood M giants

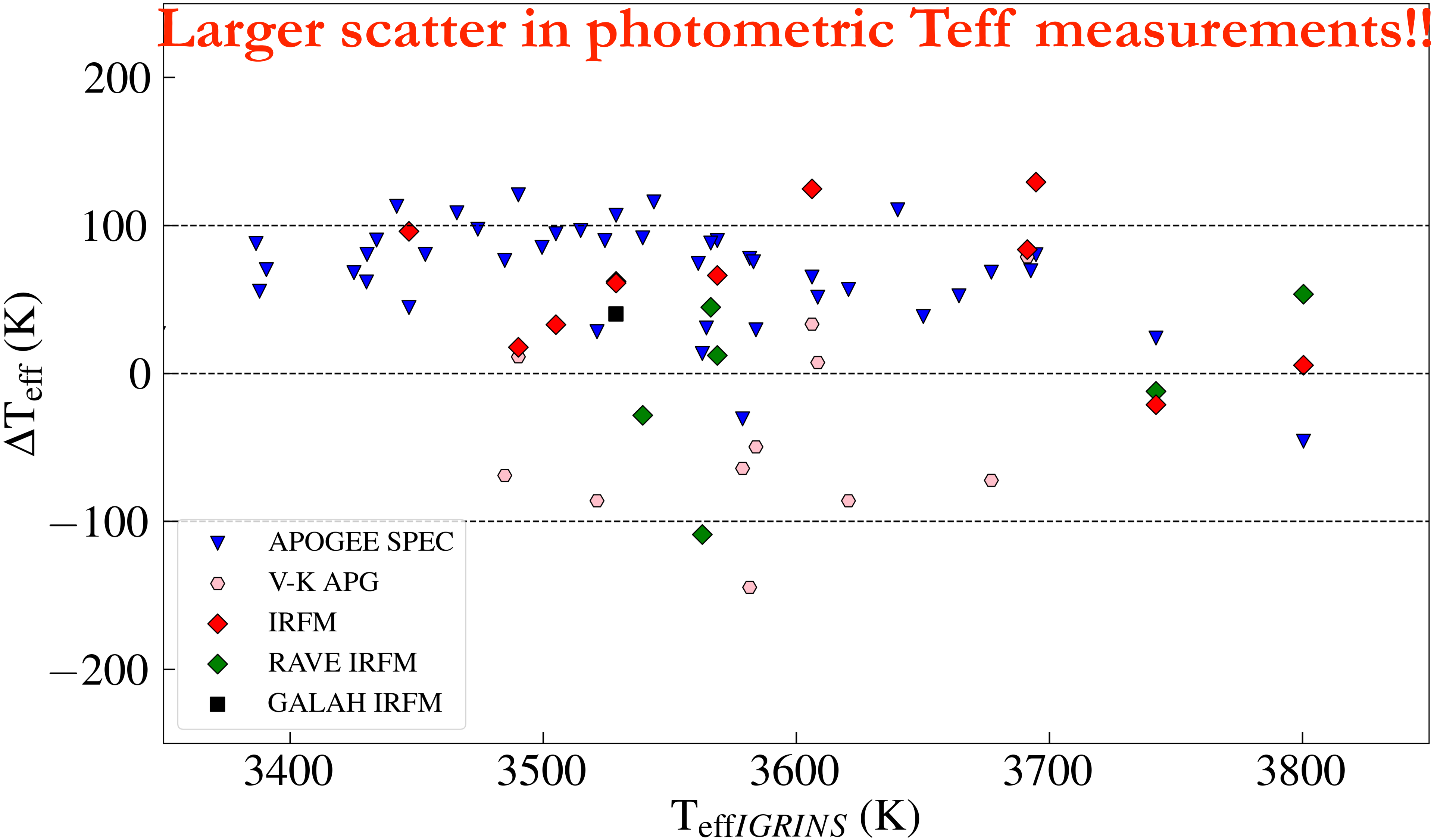
- **44 solar neighbourhood M giants** (selected from APOGEE) from our poor weather proposal with IGRINS



Teff comparison

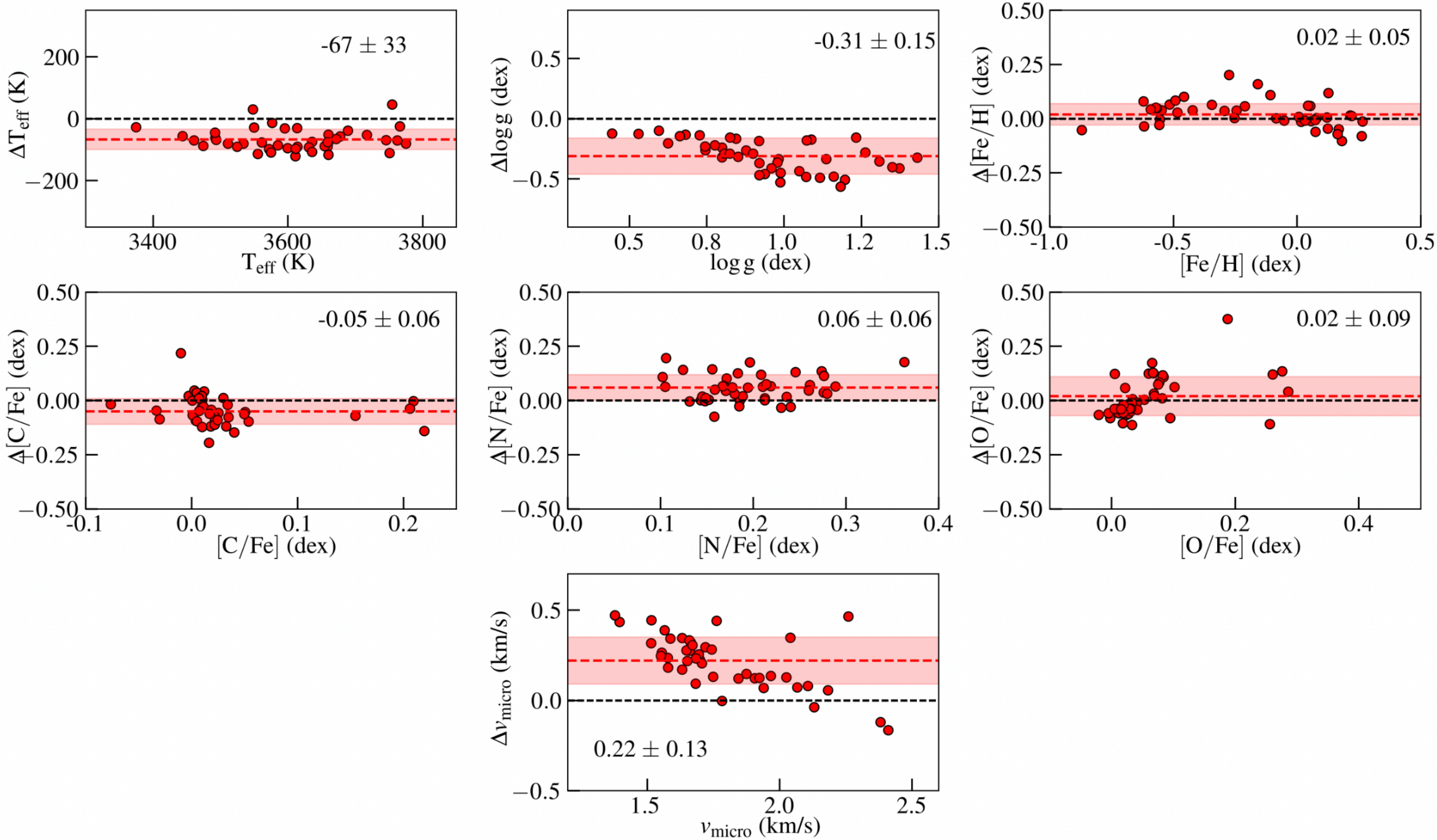
- Bessel et al (1998) Teff-$(V\text{-}K)_0$ with reddening from APOGEE

Y axis : Literature - Our method



APOGEE comparison

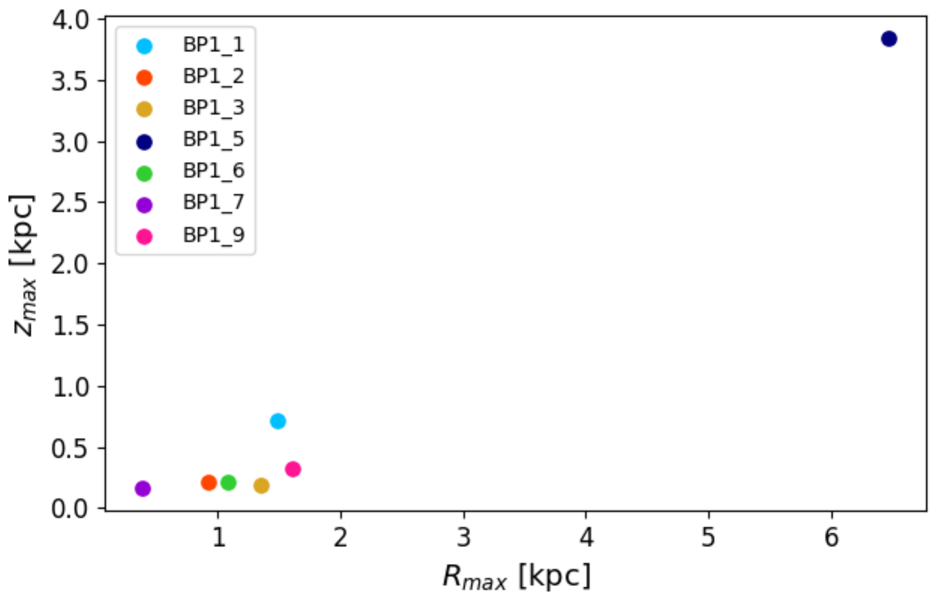
Y axis : Literature - Our method

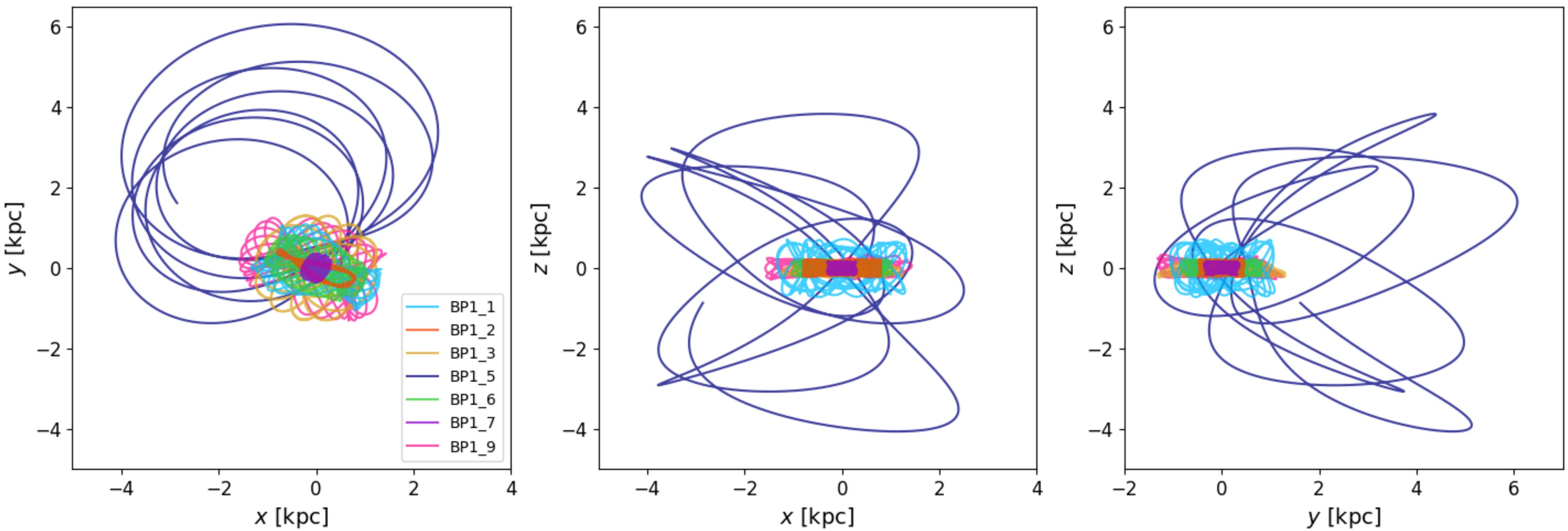


Nandakumar et al. (2023a)

BP1: orbital analysis

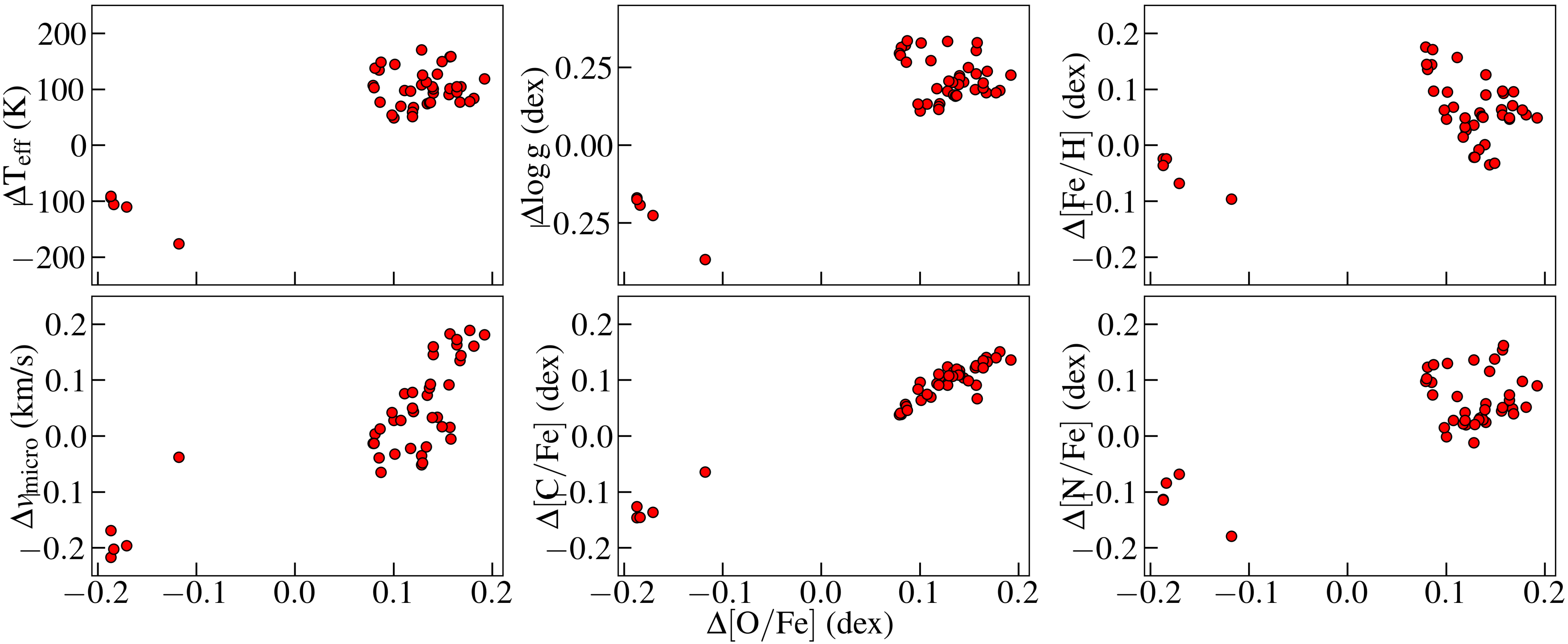
Nandakumar et al. (2024a)



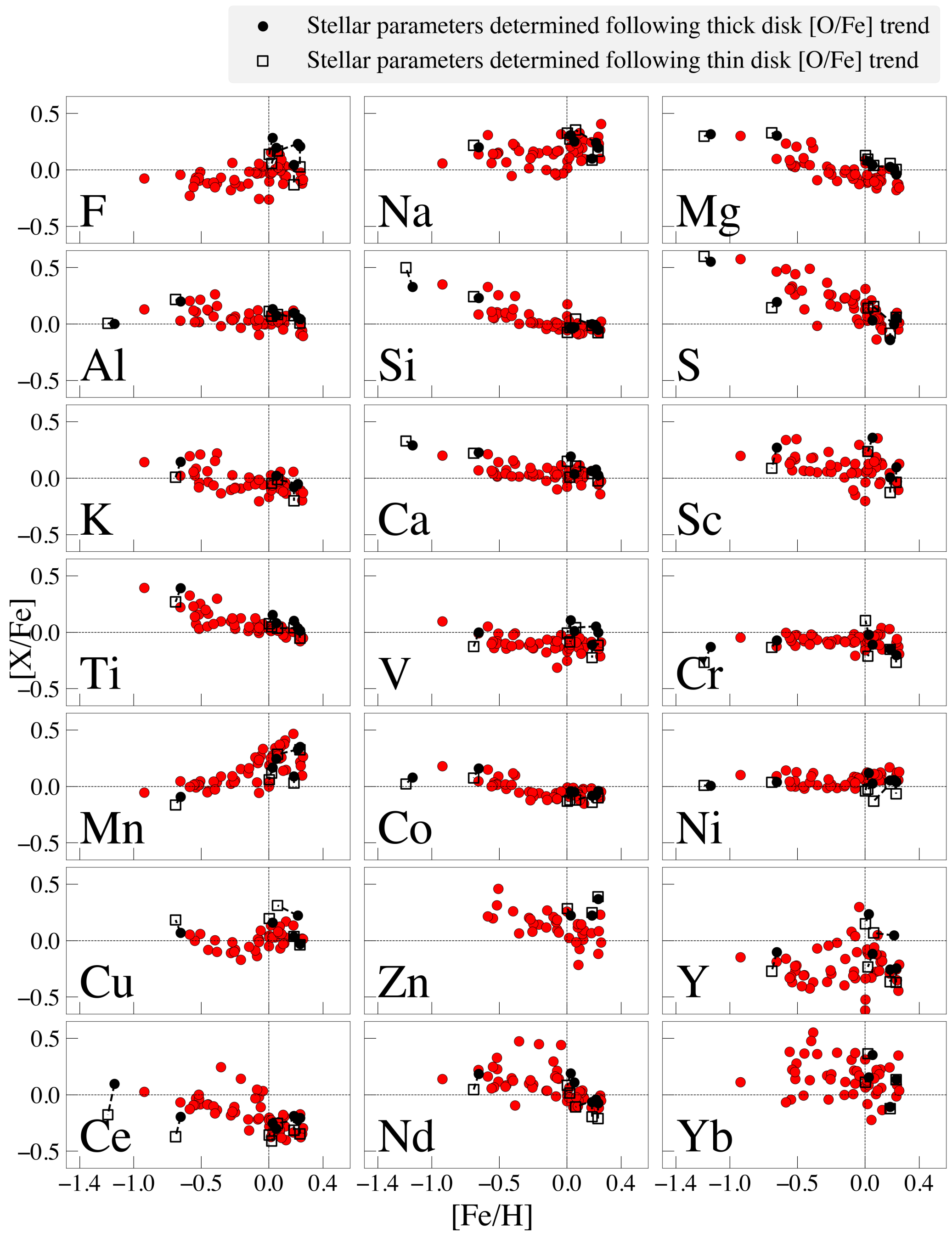


Different assumption

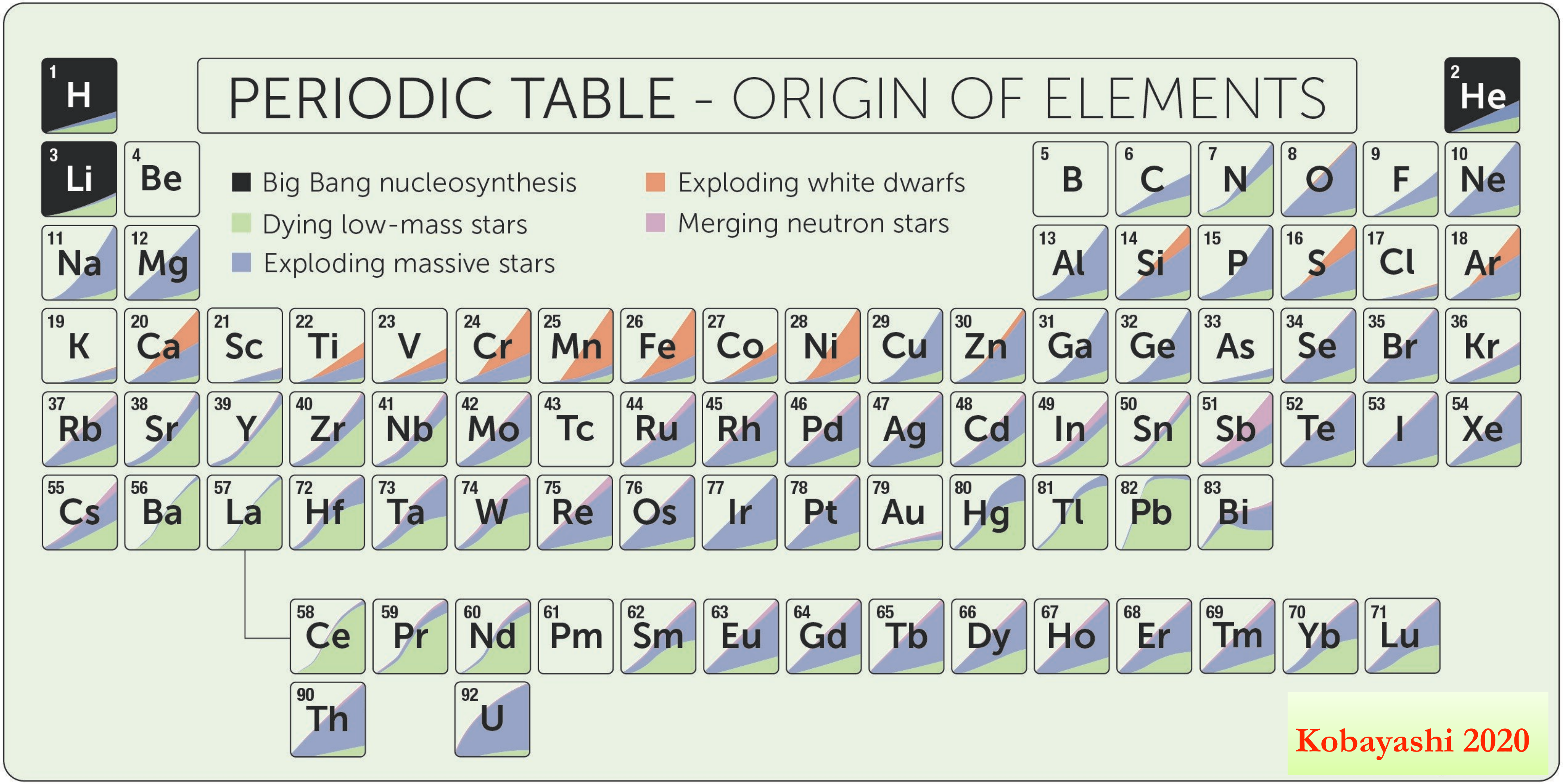
Nandakumar et al. (2023a)



BP1: thin-disc [O/Fe]

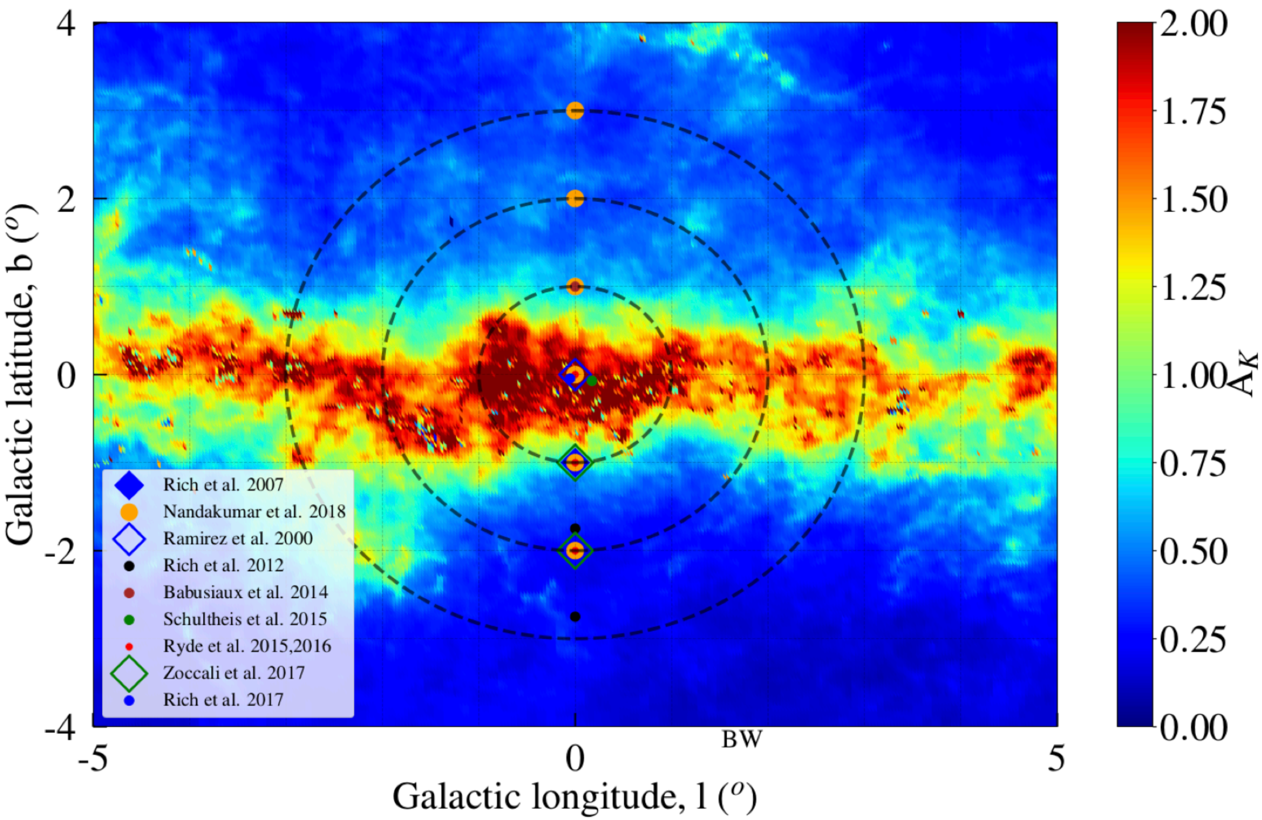


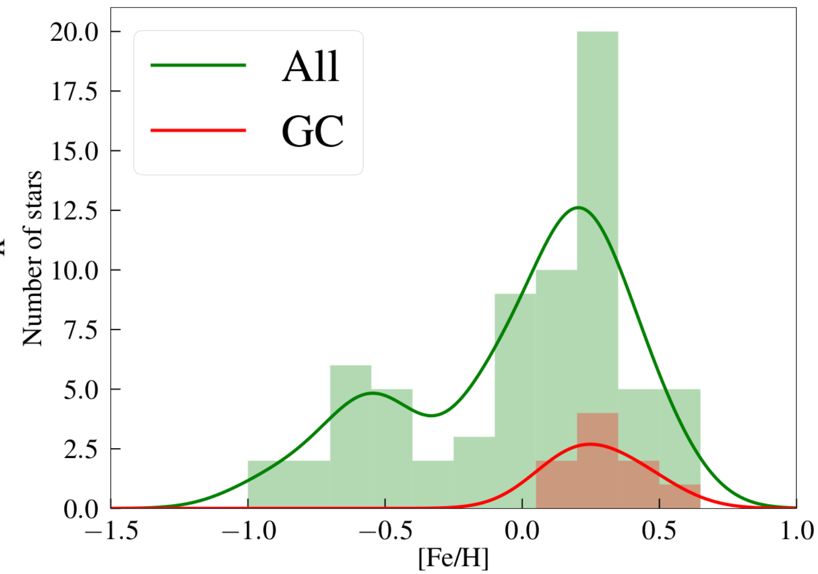
Chemical enrichment



Kobayashi 2020

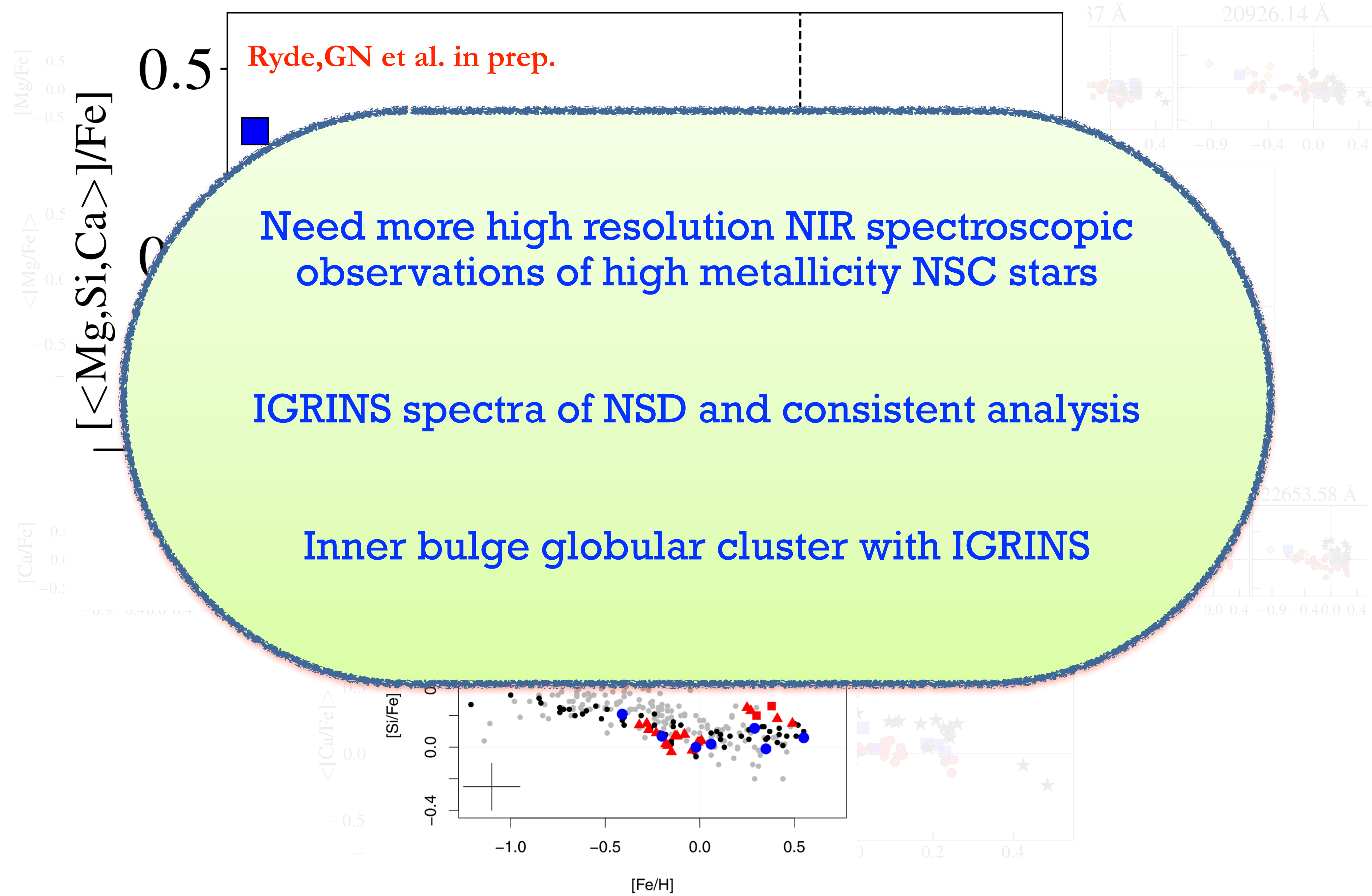
Inner Galactic bulge (IGB)





- Chemistry of inner Galactic Bulge and its connection to the outer Bulge and/or other Milky Way components??

NSC: preliminary results

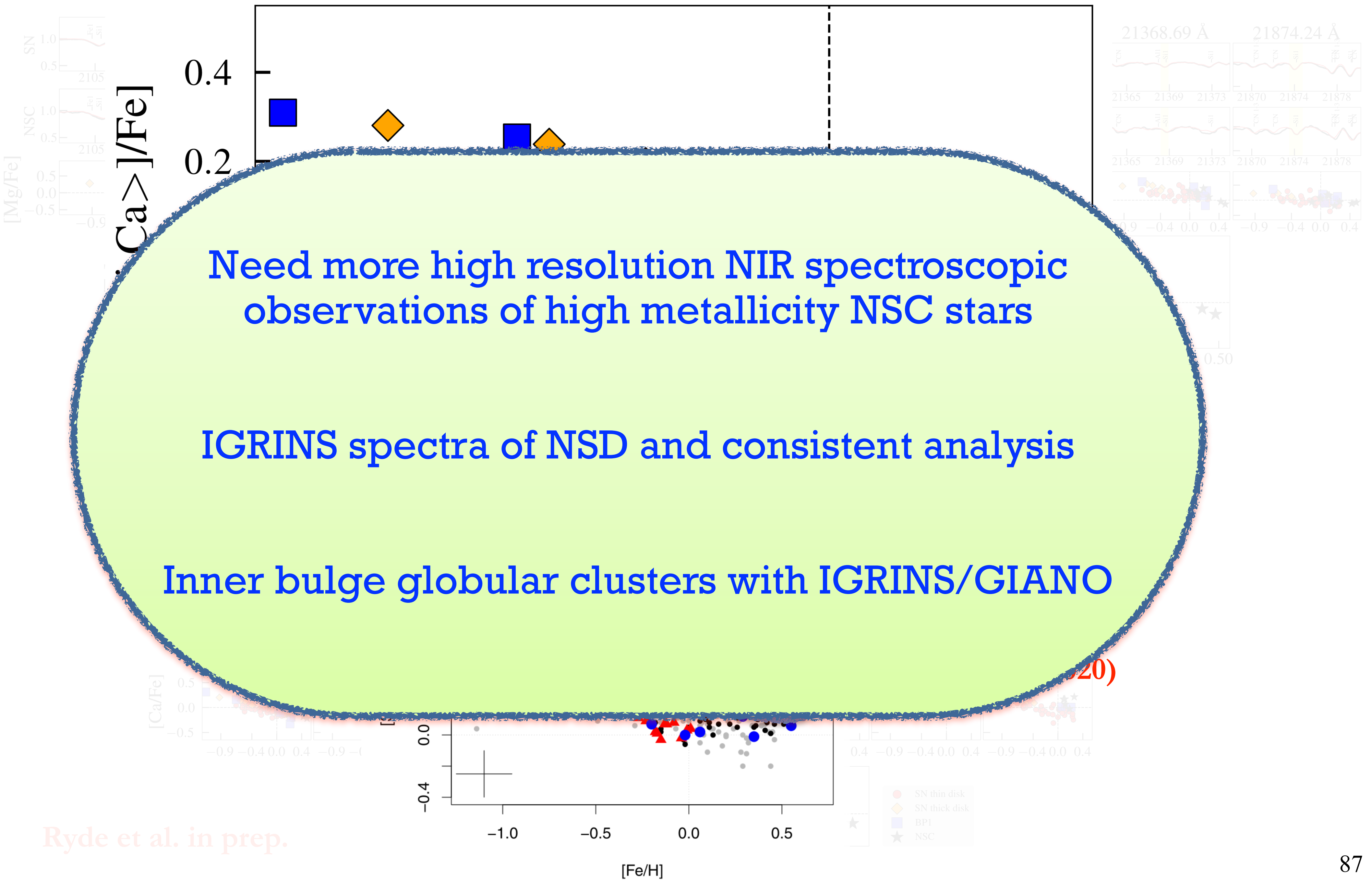


Need more high resolution NIR spectroscopic observations of high metallicity NSC stars

IGRINS spectra of NSD and consistent analysis

Inner bulge globular cluster with IGRINS

NSC: preliminary results



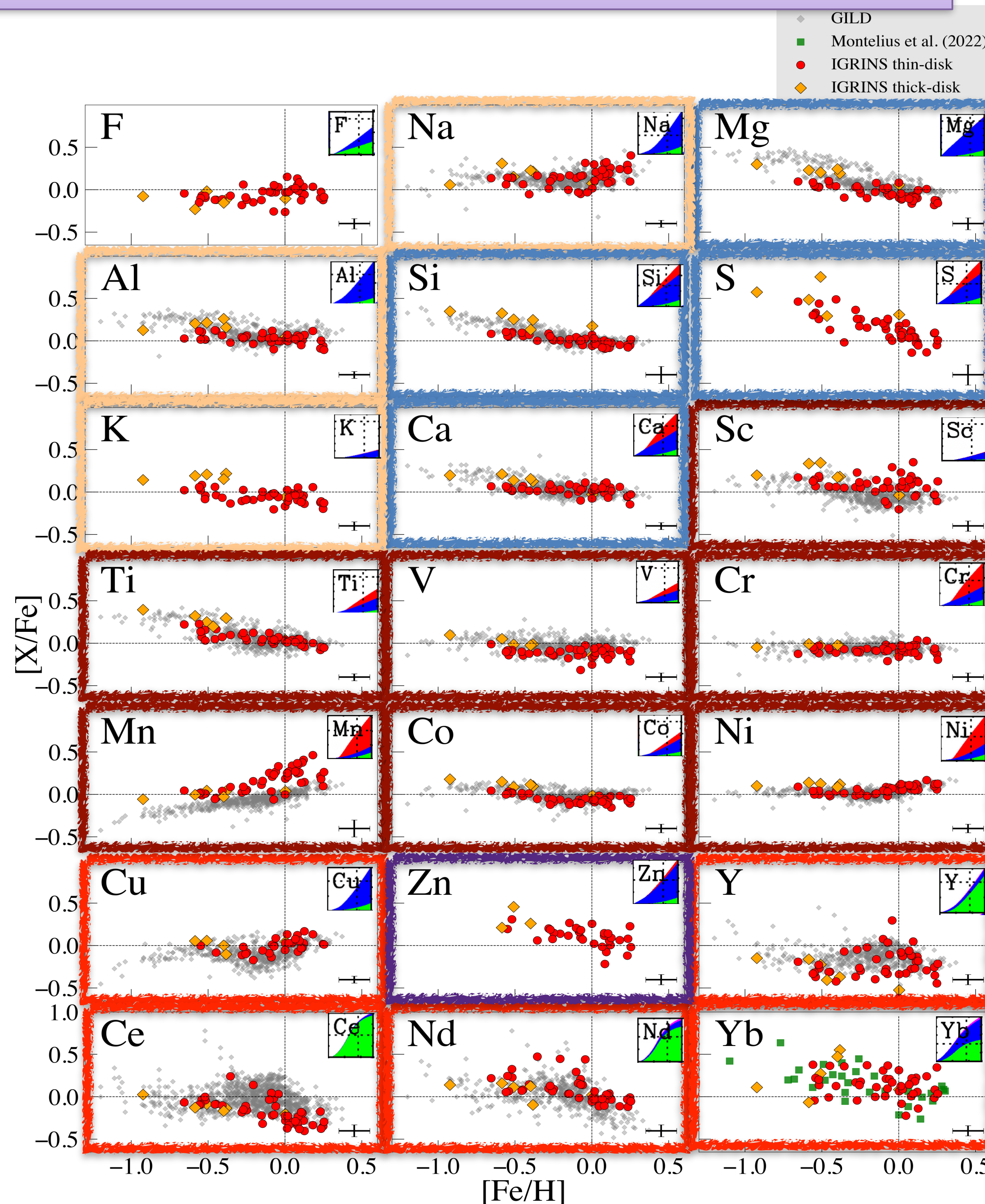
Need more high resolution NIR spectroscopic observations of high metallicity NSC stars

IGRINS spectra of NSD and consistent analysis

Inner bulge globular clusters with IGRINS/GIANO

Abundance trends: 21 elements

Nandakumar et al. (2024b)



α elements

Odd-z elements

Iron-peak elements

Between iron-peak and neutron-capture elements

Neutron-capture elements

Asymptotic Giant Branch Stars
Core−collapse Supernovae
Type Ia Supernovae
Neutron Star Mergers

Kobayashi et al. (2020)