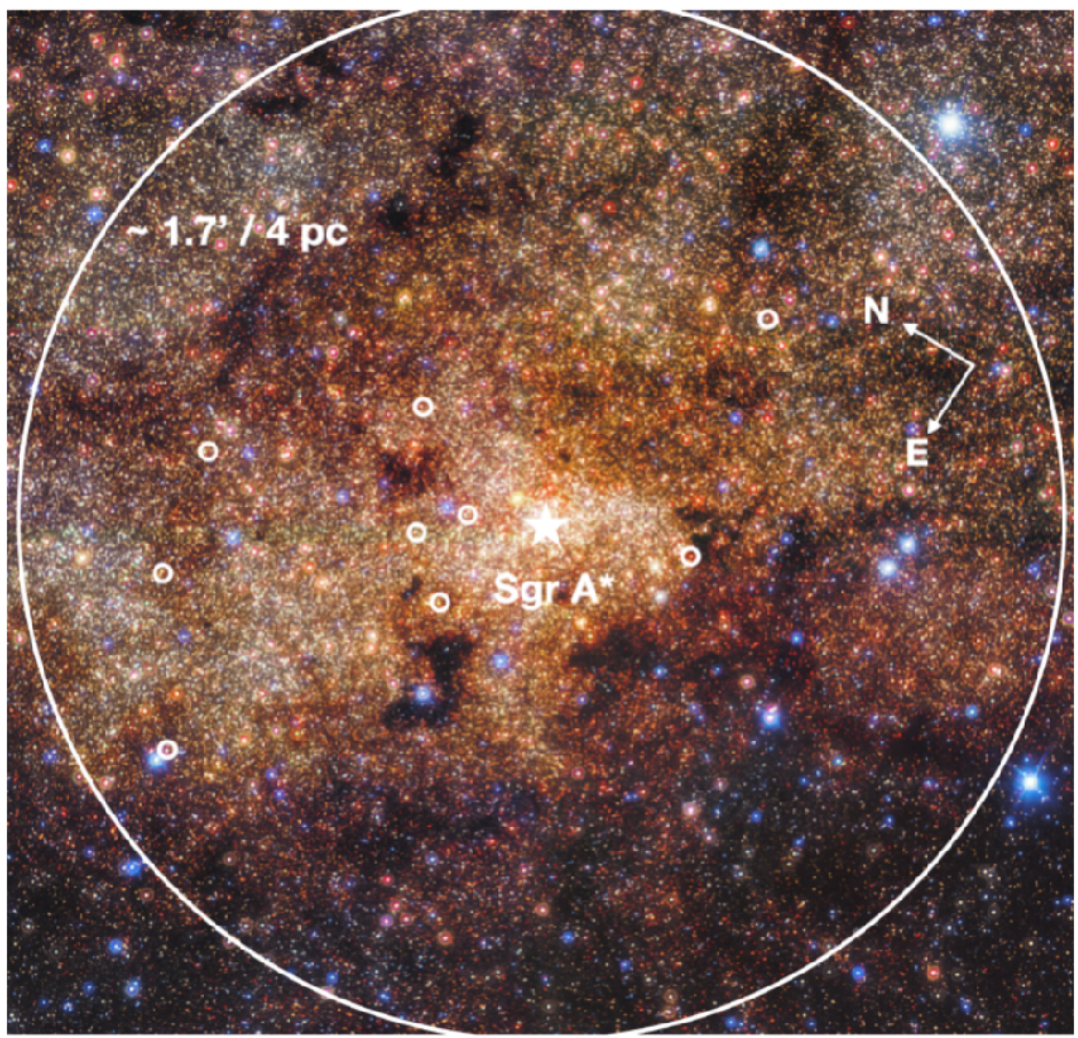
Chemical characterisation of the Galactic Center



Essential for unraveling

- formation of NSC, NSD
- relationships between different structures and the galaxy as a whole
- roles of galactic nuclei in galaxy formation and evolution

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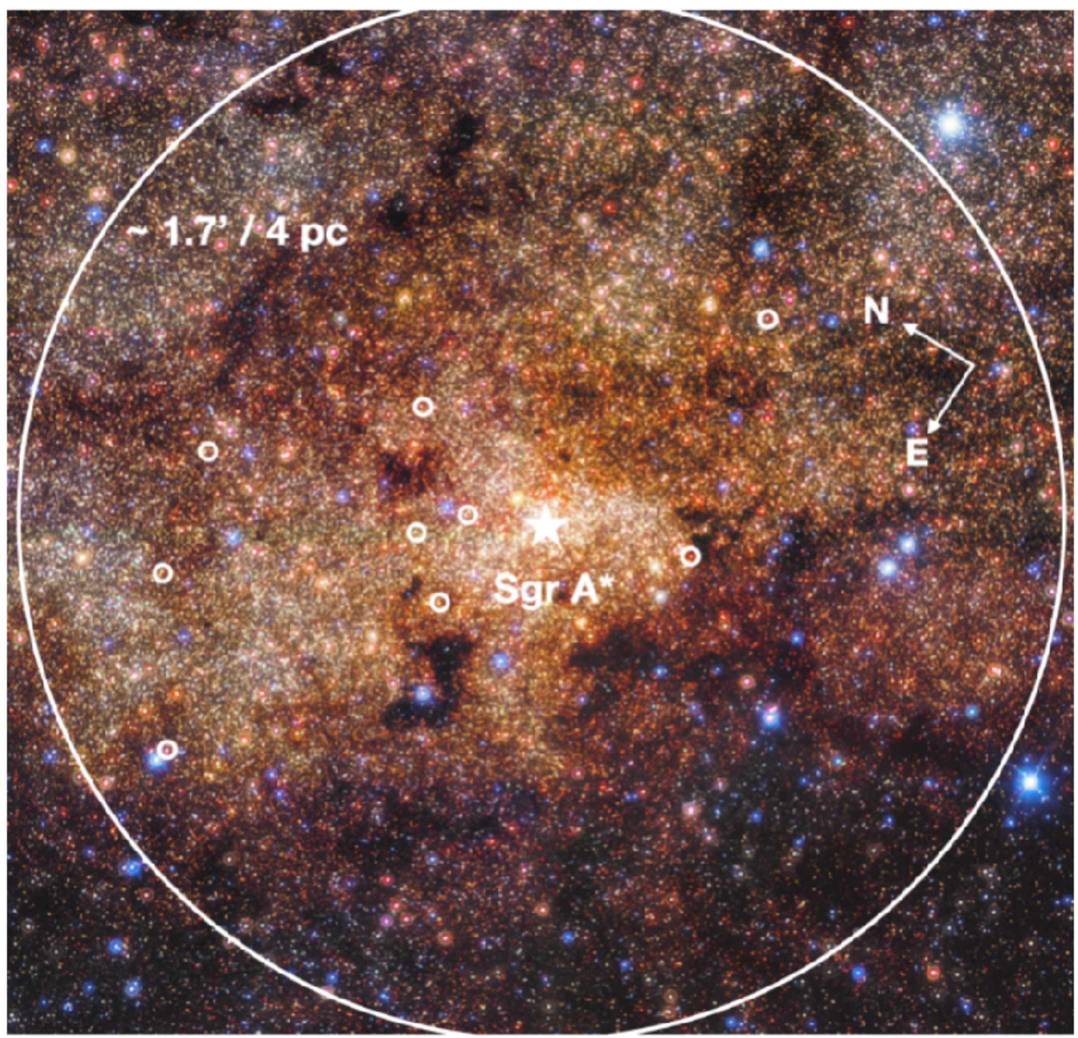
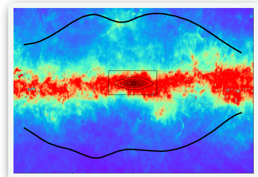


Essential for unraveling
- formation of NSC, NSD
- relationships between different structures and the galaxy as a whole
- roles of galactic nuclei in galaxy formation and evolution

Galactic nuclei
- very bright objects
- unique environment
(strong magnetic fields, dense gas, and high turbulence)

Chemical characterisation of the Galactic Center



- **Inner bulge, Nuclear Stellar Disk, and Nuclear Star Cluster**
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  Talk by Govind Nandakumar
- **Abundances of 24 elements of the Galactic Center with IGRINS**
- **Neutron-capture elements in the near-IR**

Nils Ryde
G. Nandakumar, G. Mace, M. Schultheis, R.M. Rich, B. Thorsbro

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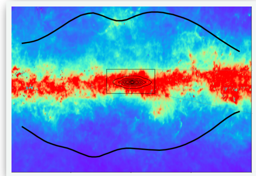

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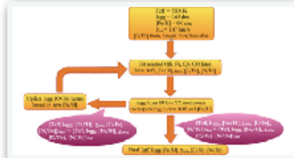

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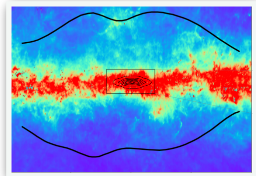

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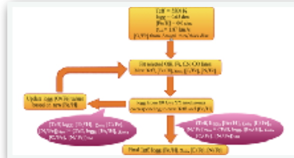

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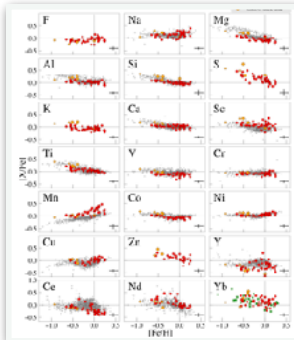

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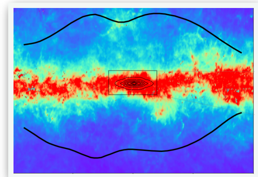
Observatoire de la CÔTE d'AZUR

Chemical characterisation of the Galactic Center

LUND UNIVERSITY



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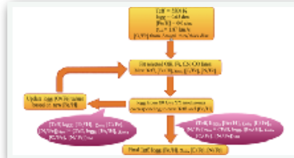

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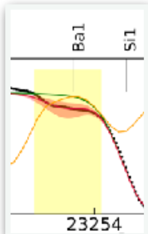

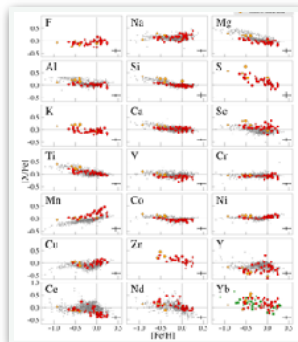

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Chemical characterisation of the Galactic Center

- Central light excess: nuclear stellar disk (120 pc), NSC (4 pc), disk of young stars (0.5 pc).[1]

- Motivation:

  - Relation between formation history of NSC and that of the Milky Way as a whole,

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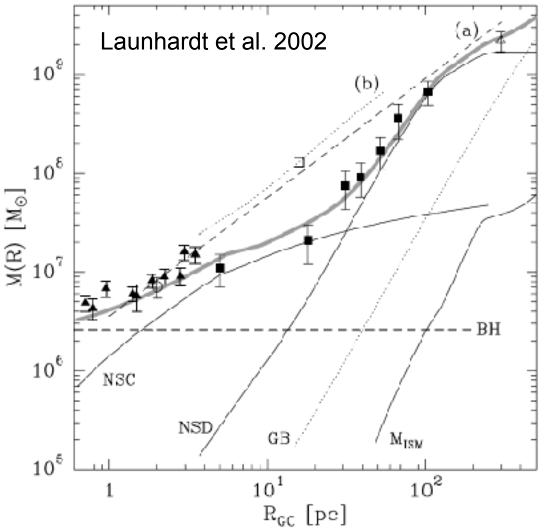

[1] "Nuclear Stellar Discs" Schultheis, Sormani, Gadotti A&ARA 2025

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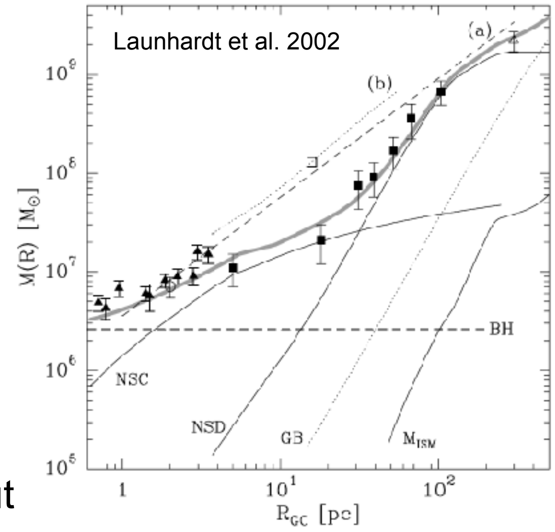

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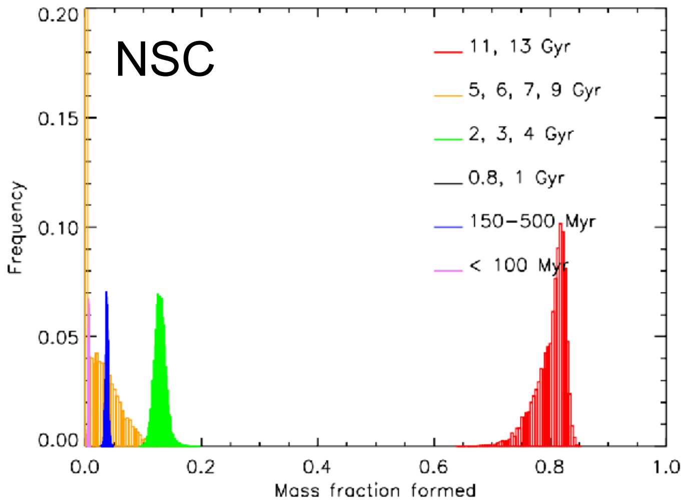
K band luminosity function fitting with BASTi isochrones:



Schödel et al. 2020; Nogueras-Lara et al. 2021

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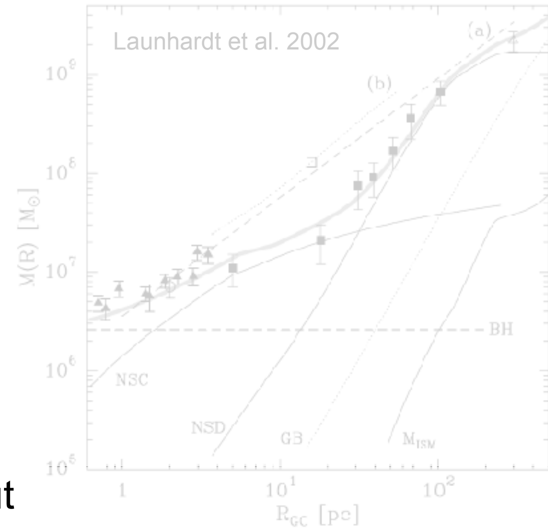

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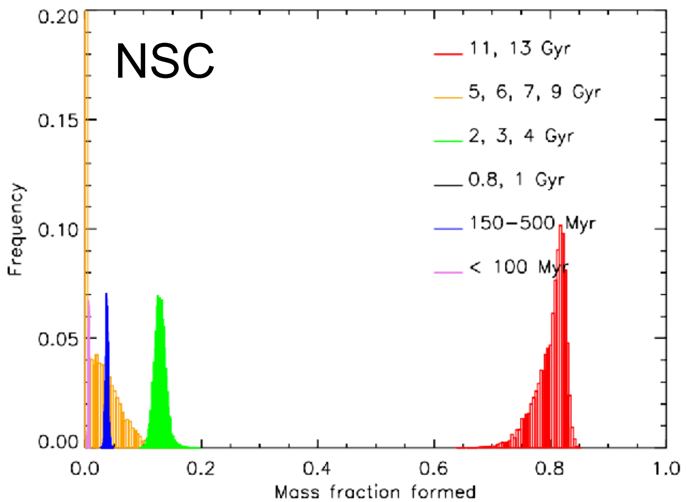

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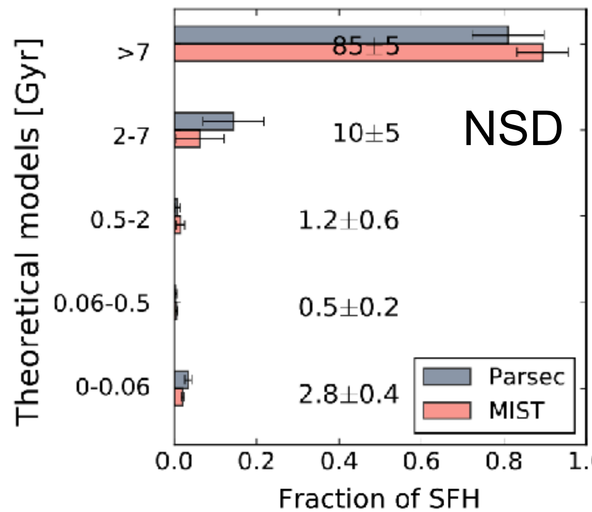

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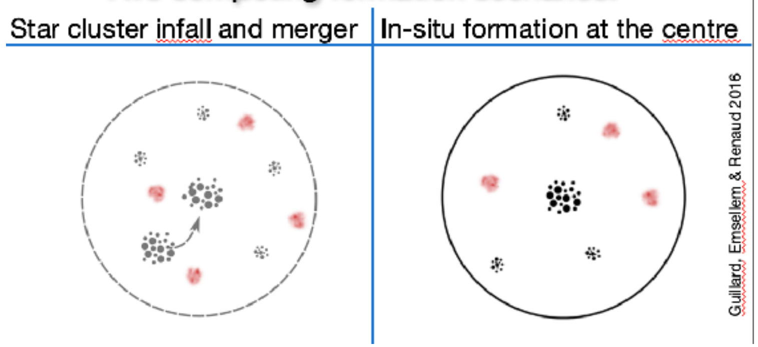
- Formation routes of NSC (Neumayer et al. 2020):
  - Infall and merging of globular clusters over time *or*
  - In situ formation due to inward migration of gas and clusters originating in the early disk

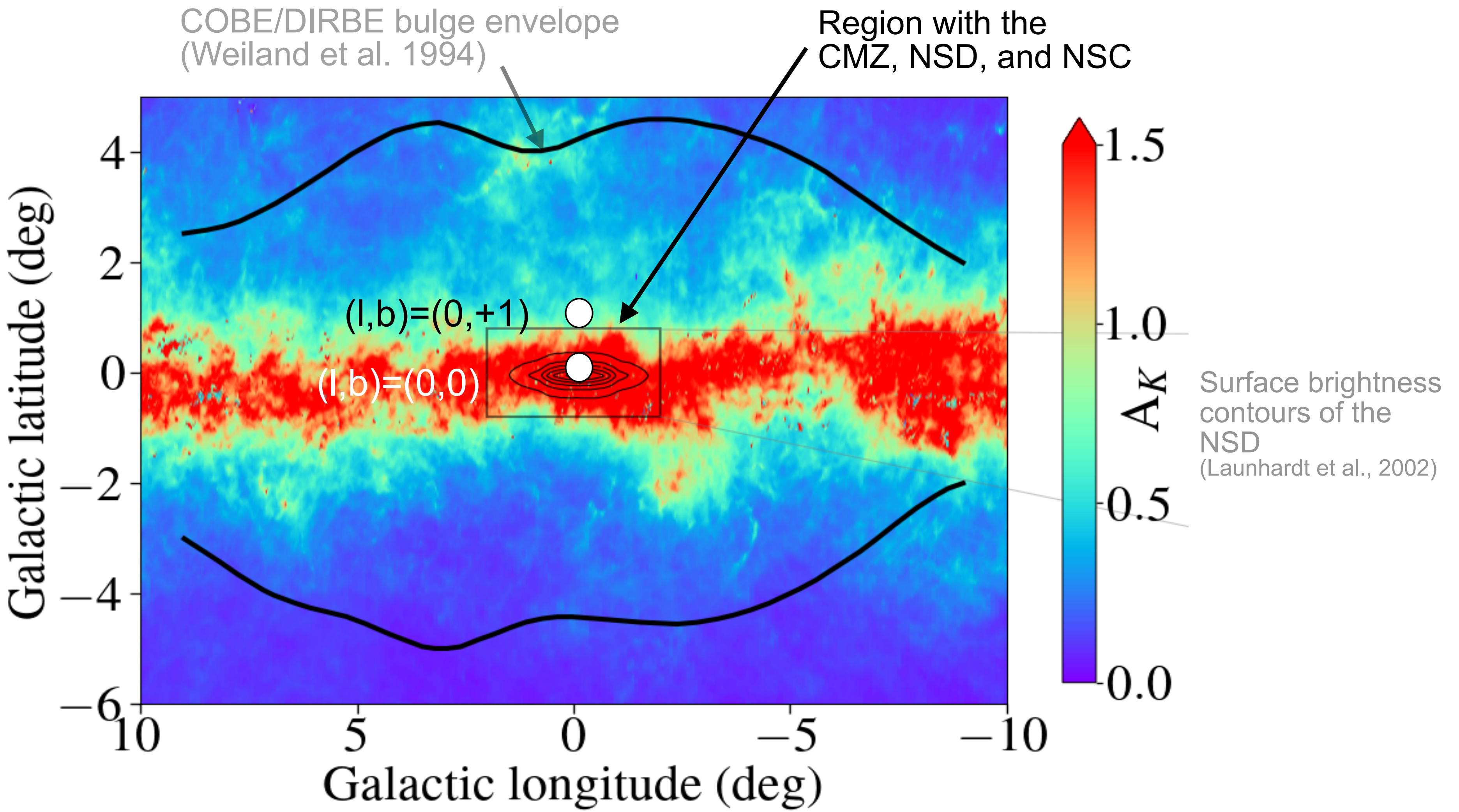
Two competing formation scenarios:



- Connection NSC/NSD/Bulge? Unique SFH? Highest stellar densities in the MW

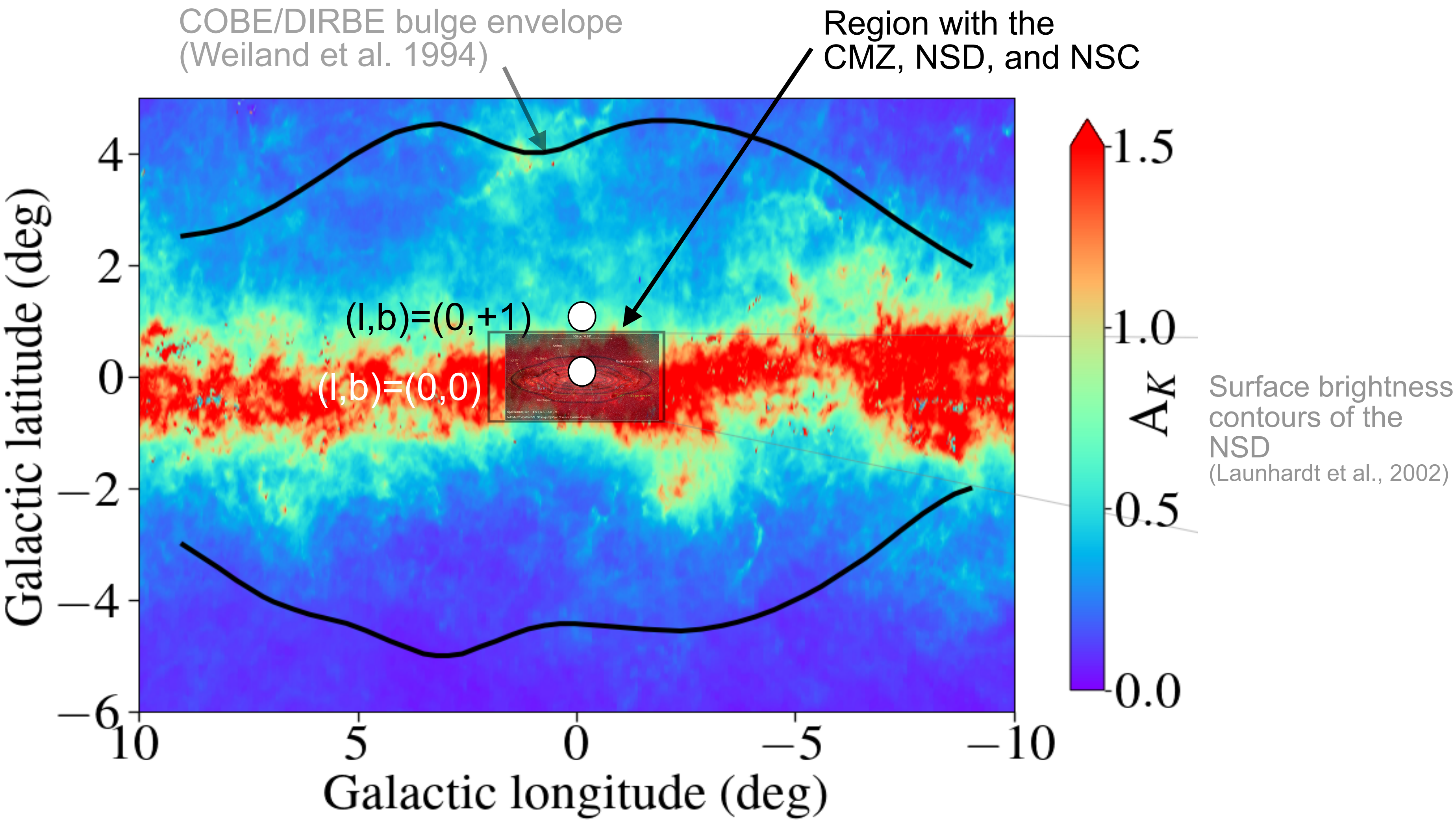
- Detailed chemistry is needed

Chemical characterisation of the Galactic Center



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

Chemical characterisation of the Galactic Center



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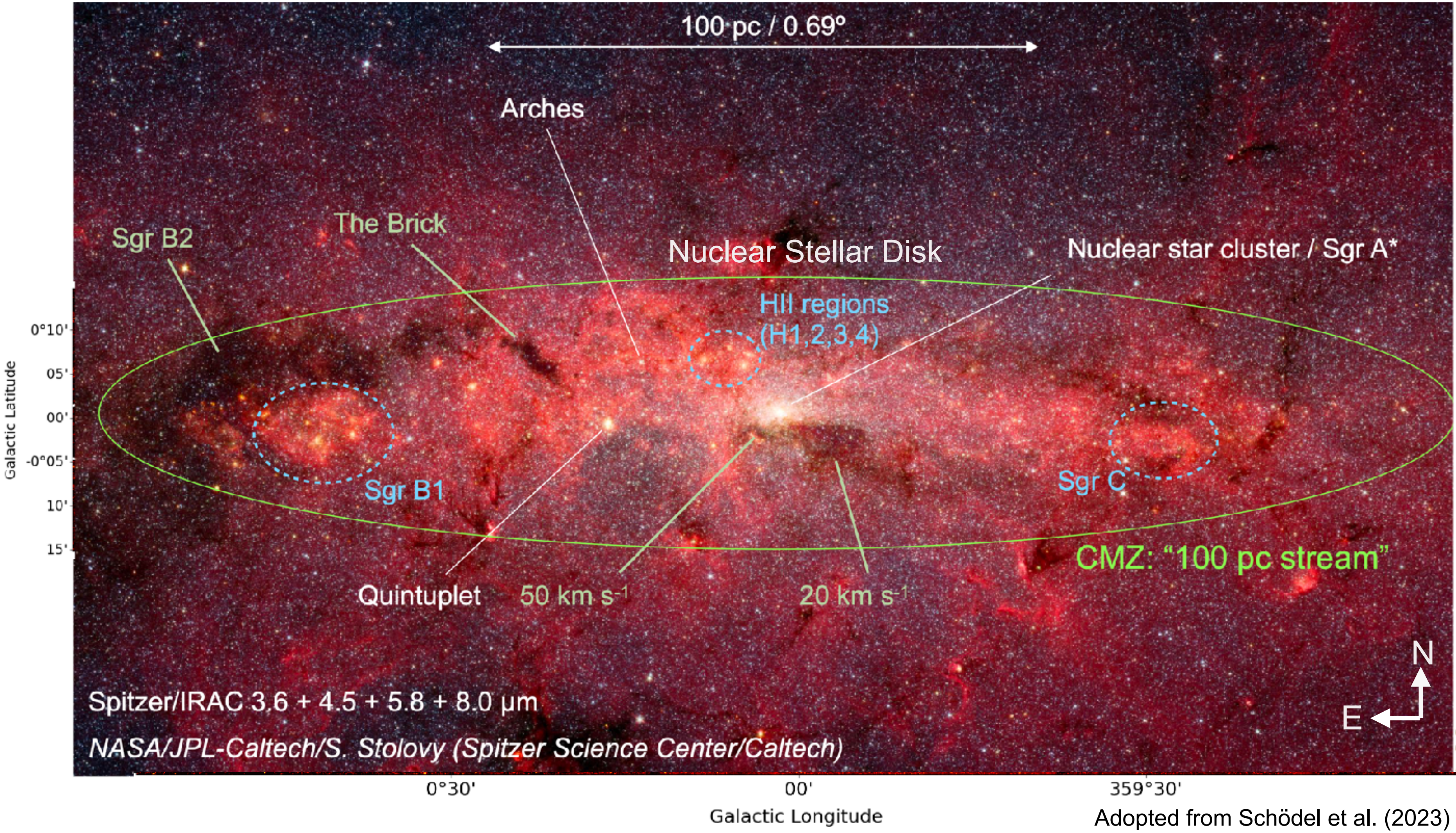

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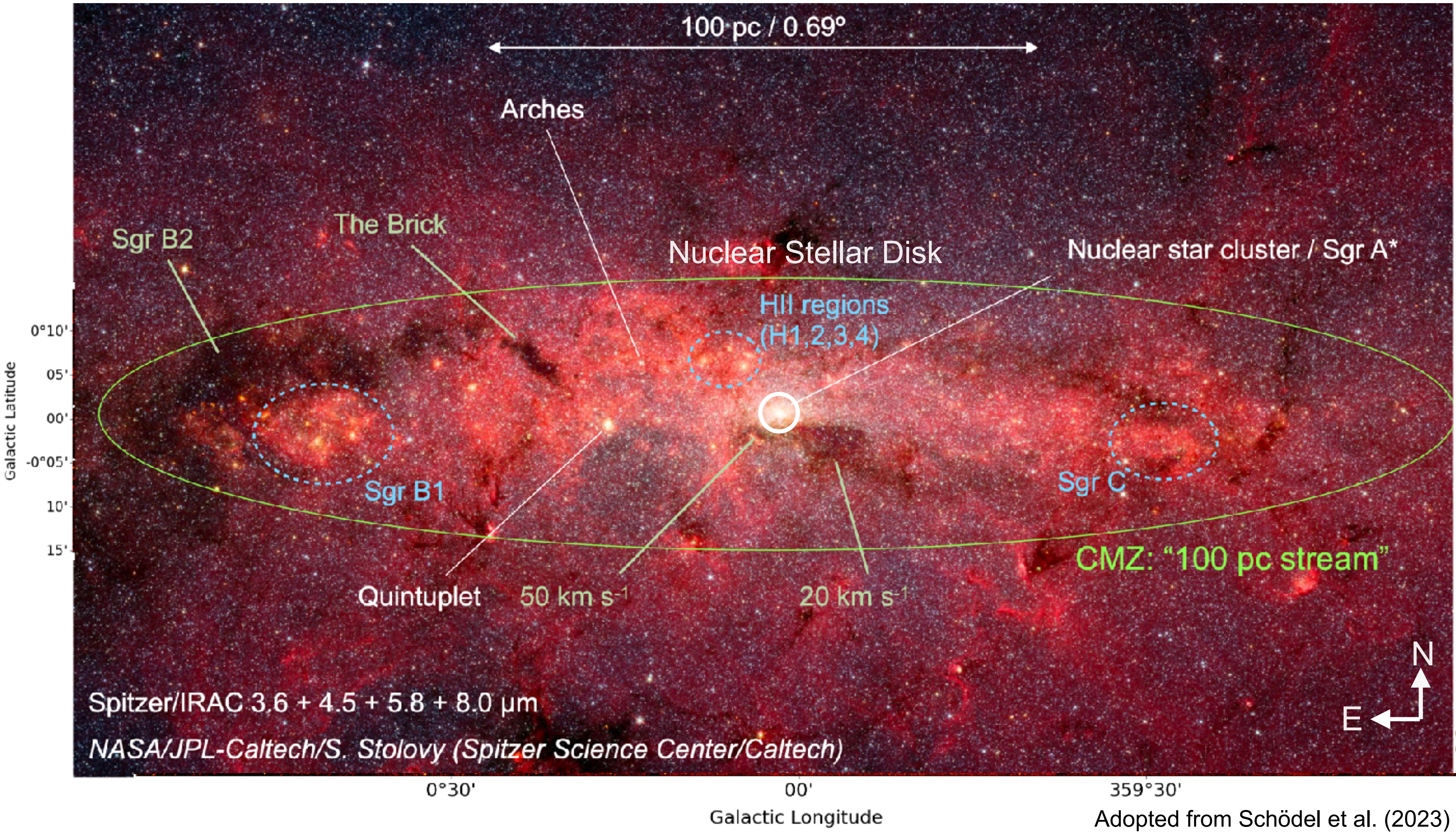

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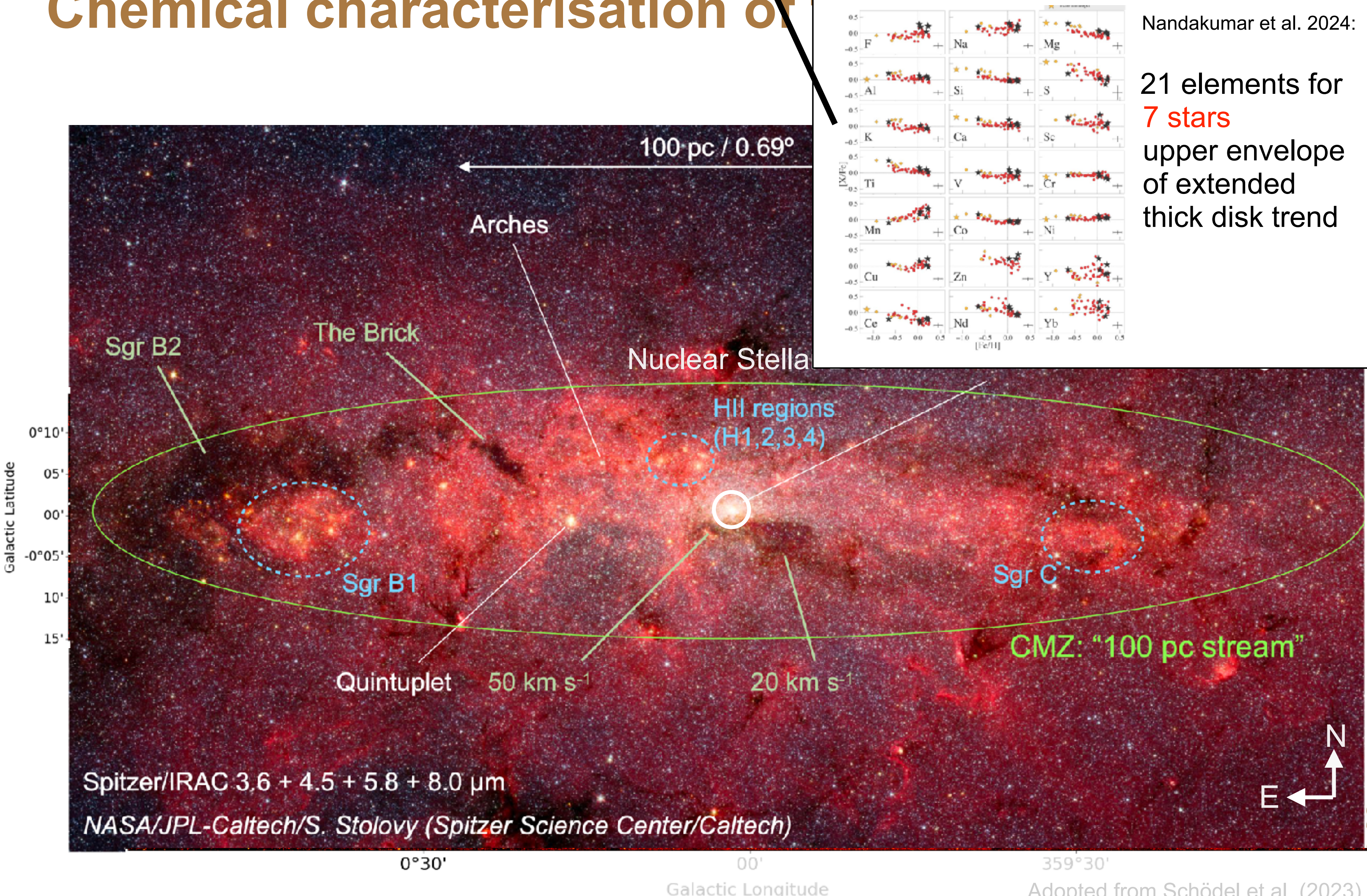
Chemical characterisation of

1° N

Detailed abundances (*l*,*b*) = (0,+1)

Nandakumar et al. 2024:

21 elements for 7 stars upper envelope of extended thick disk trend



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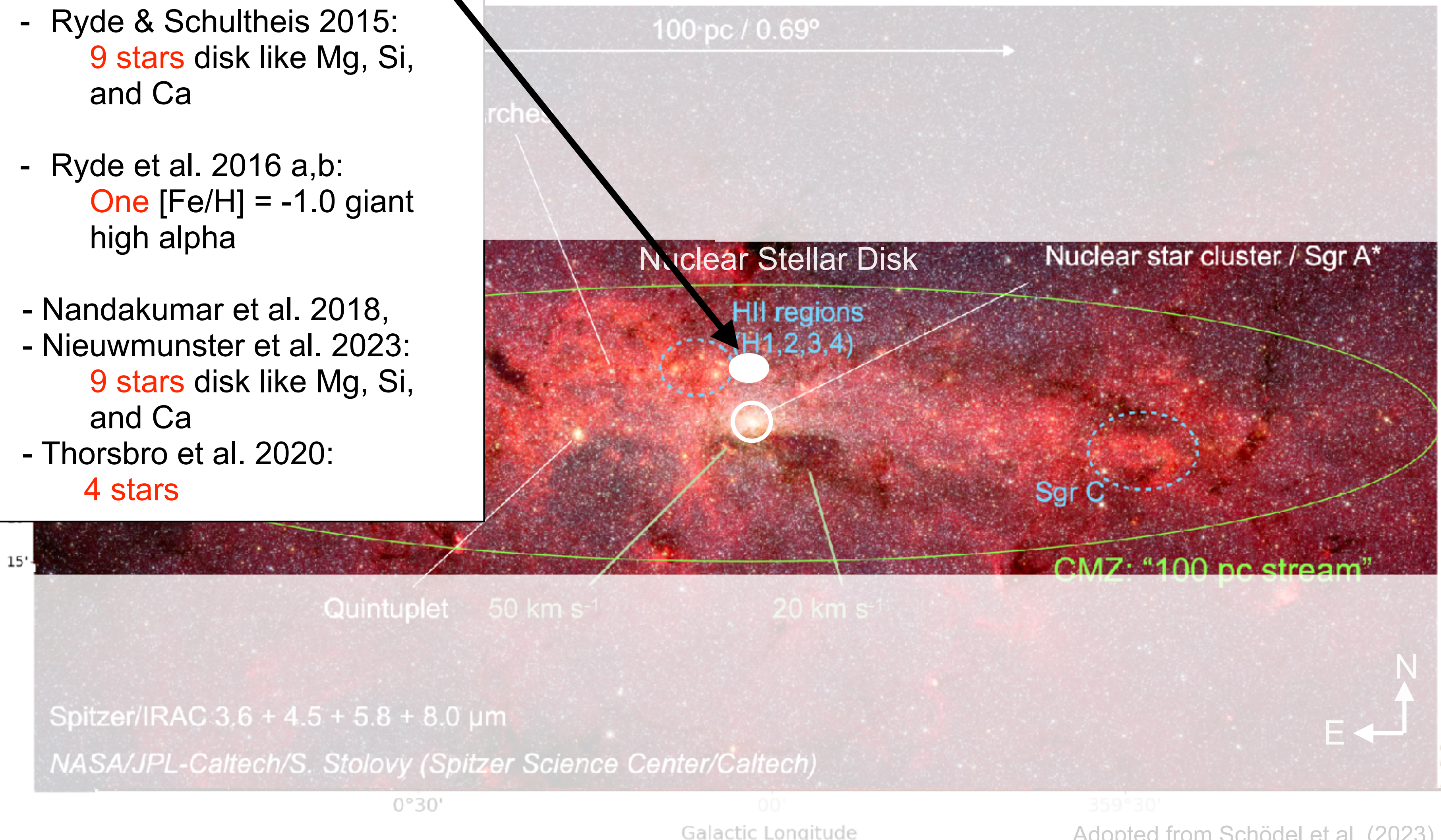
Chemical characterisation of the Galactic Center

Detailed abundances NSD:

- Ryde & Schultheis 2015:
  9 stars disk like Mg, Si, and Ca
- Ryde et al. 2016 a,b:
  One [Fe/H] = -1.0 giant high alpha
- Nandakumar et al. 2018,
- Nieuwmunster et al. 2023:
  9 stars disk like Mg, Si, and Ca
- Thorsbro et al. 2020:
  4 stars



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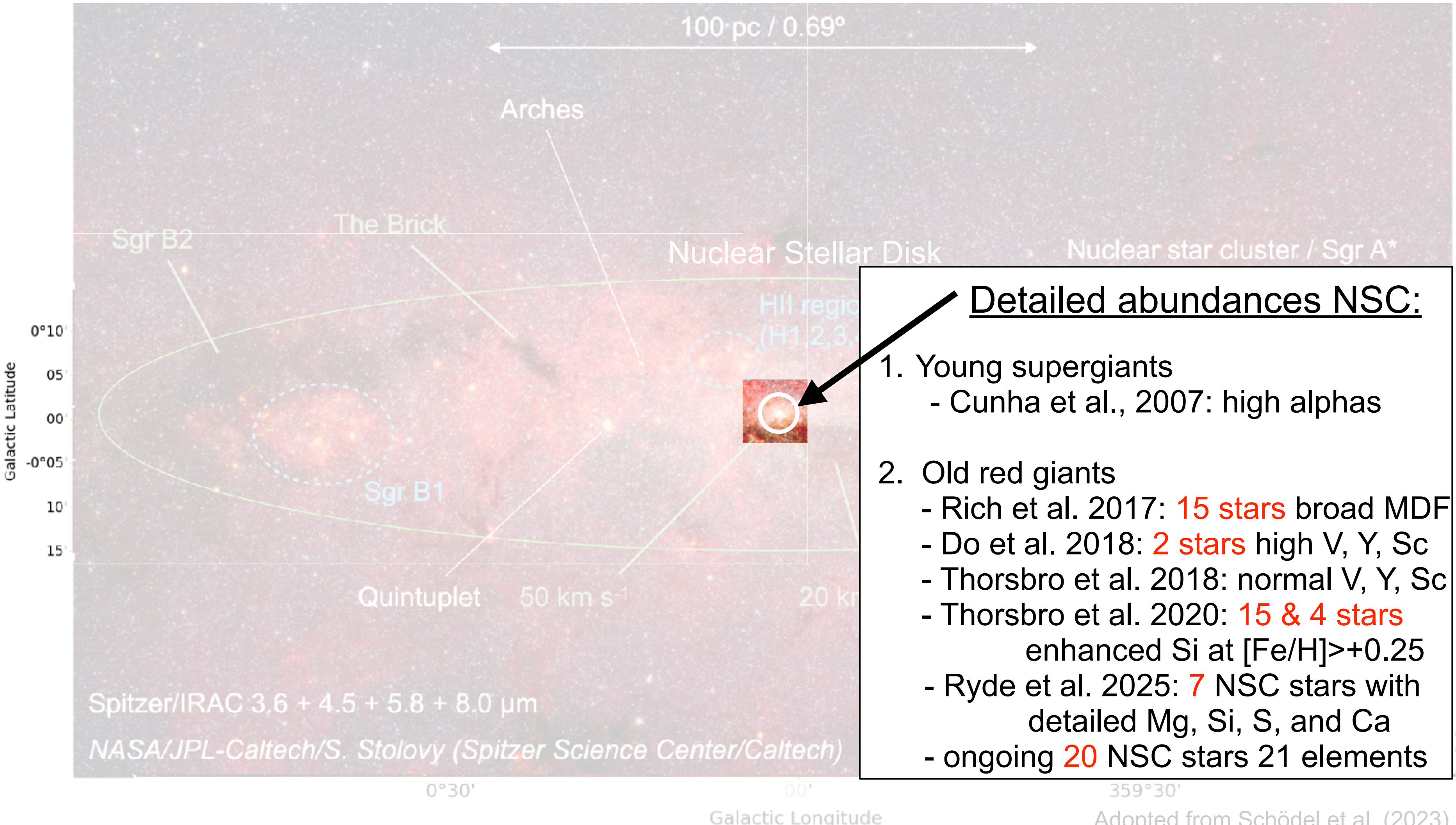

Detailed abundances NSC:

1. Young supergiants
   - Cunha et al., 2007: high alphas
2. Old red giants
   - Rich et al. 2017: 15 stars broad MDF
   - Do et al. 2018: 2 stars high V, Y, Sc
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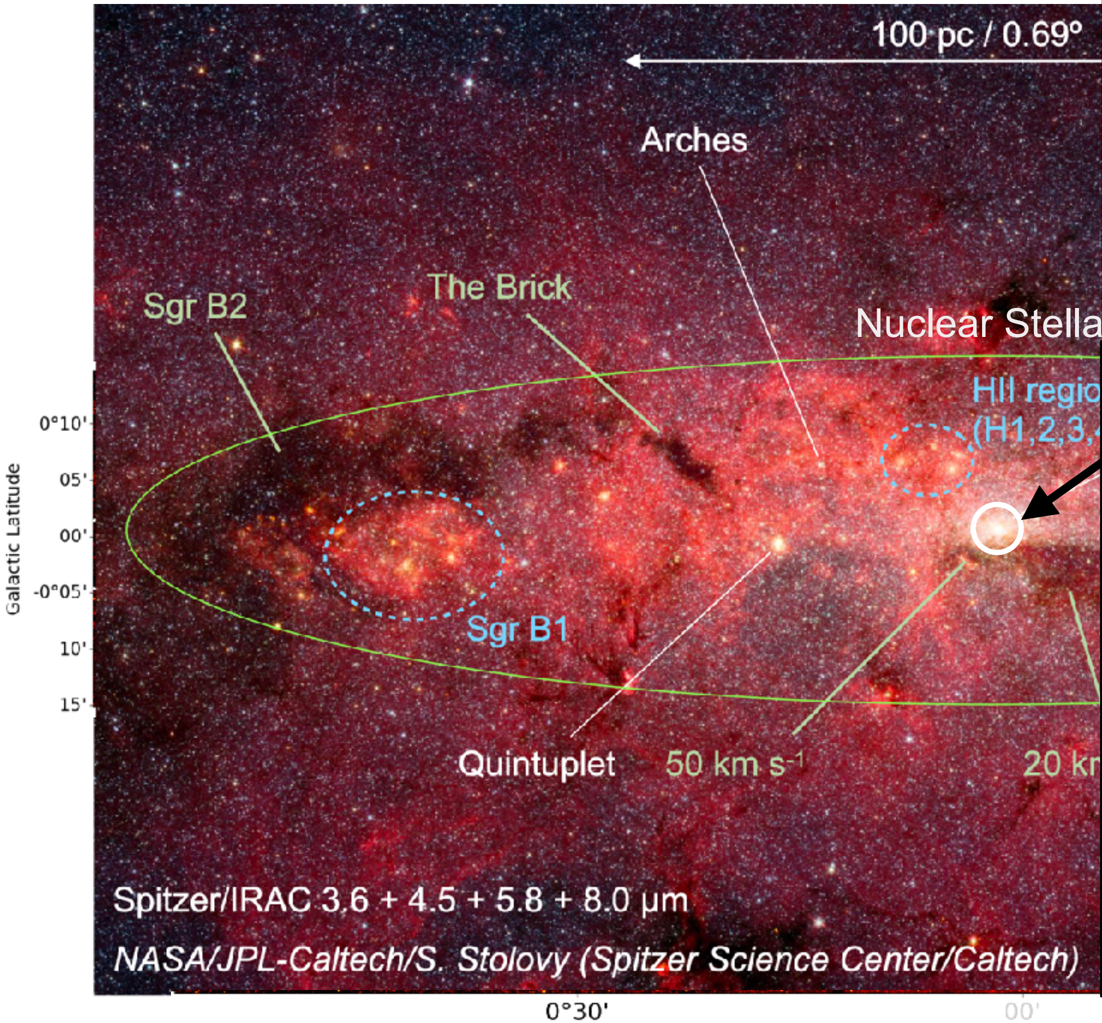

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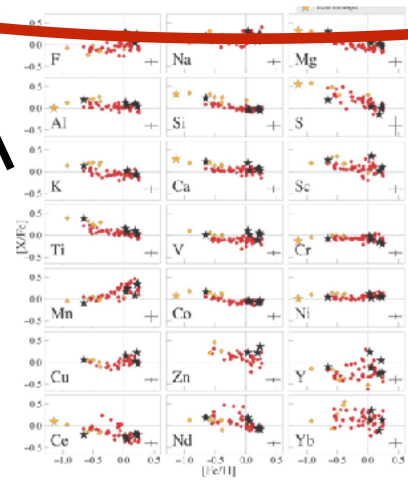

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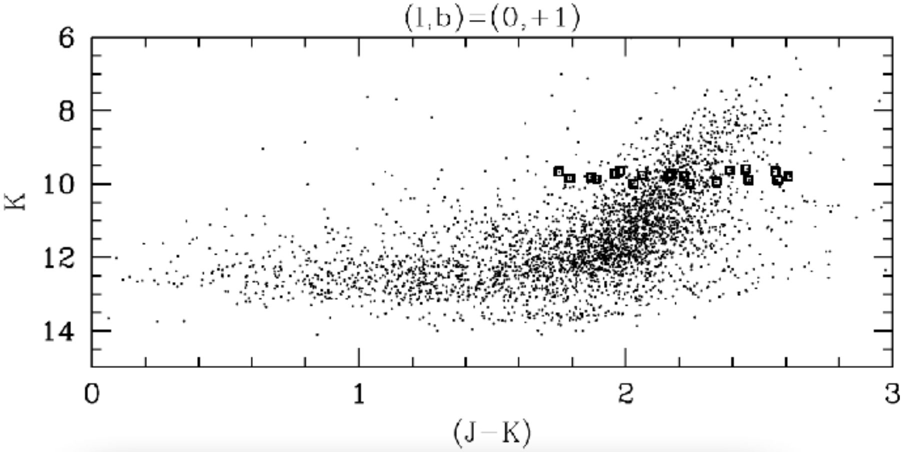
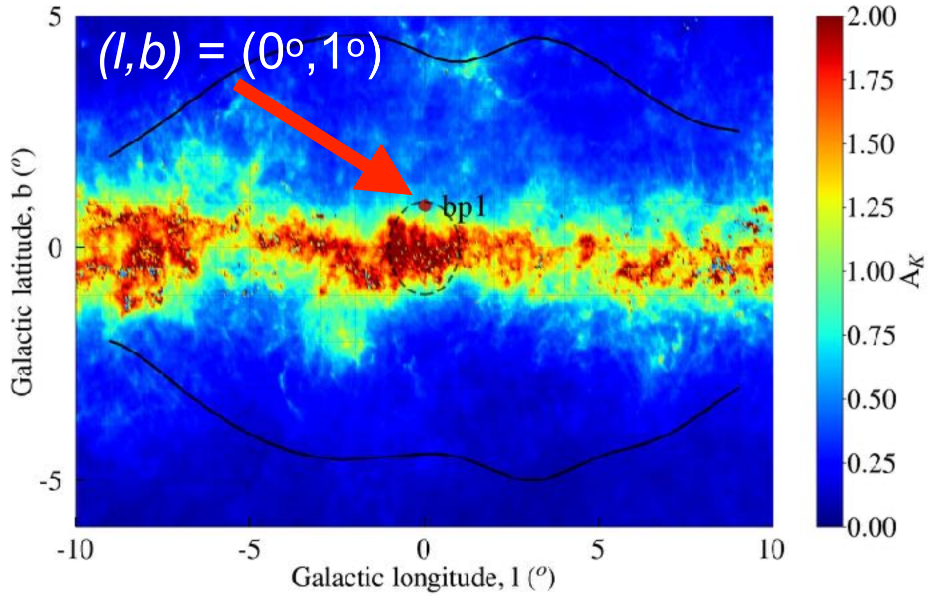
Differential analysis of SN, inner bulge, and NSC

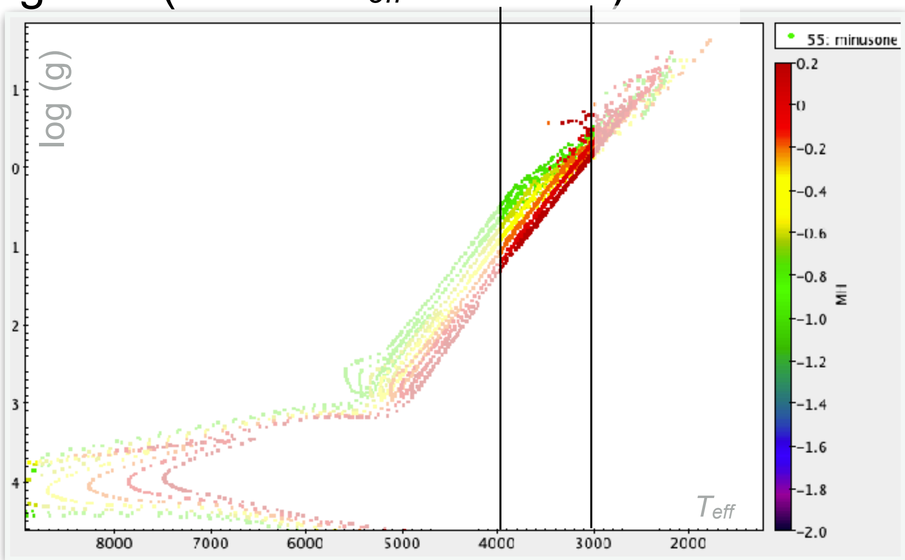
Chemical characterisation of the Galactic Center

a. *(l,b)* = (0°,1°) North of the Center





- M giants (3250 < T_{eff} < 4000 K) needed



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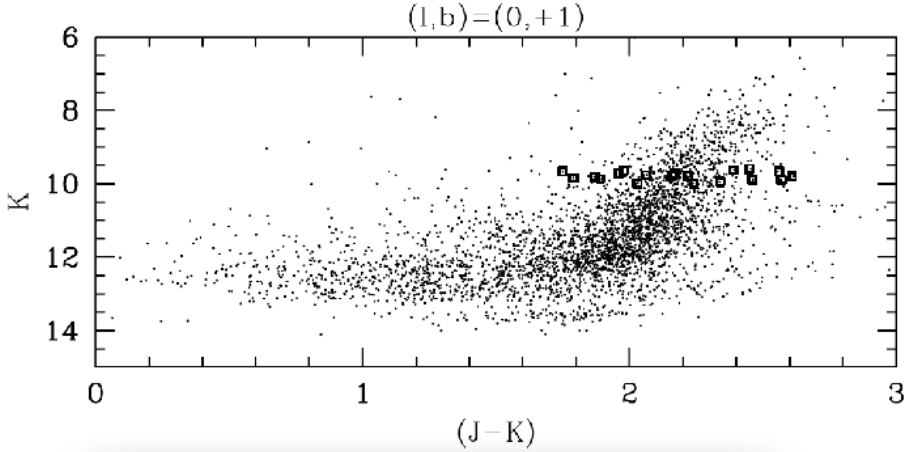
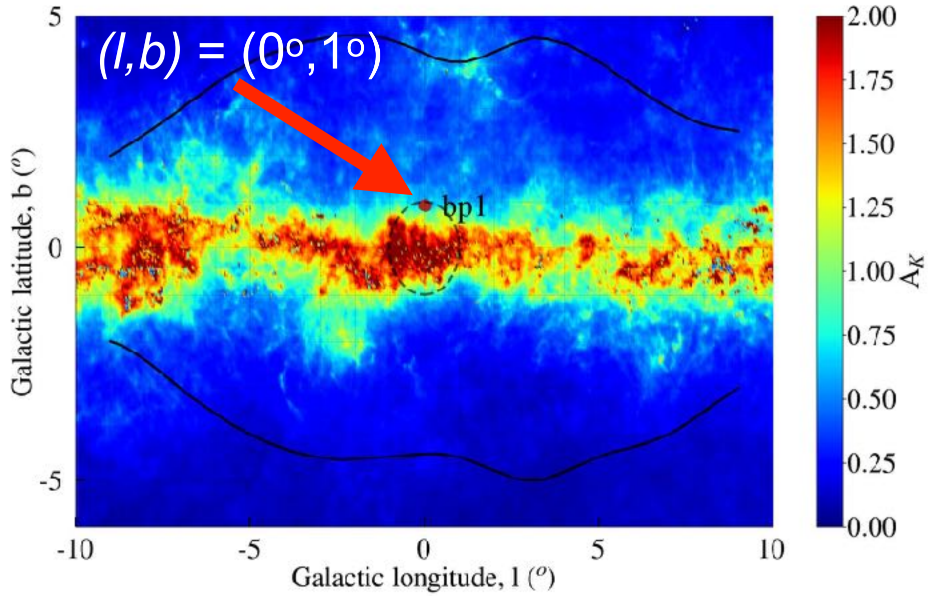


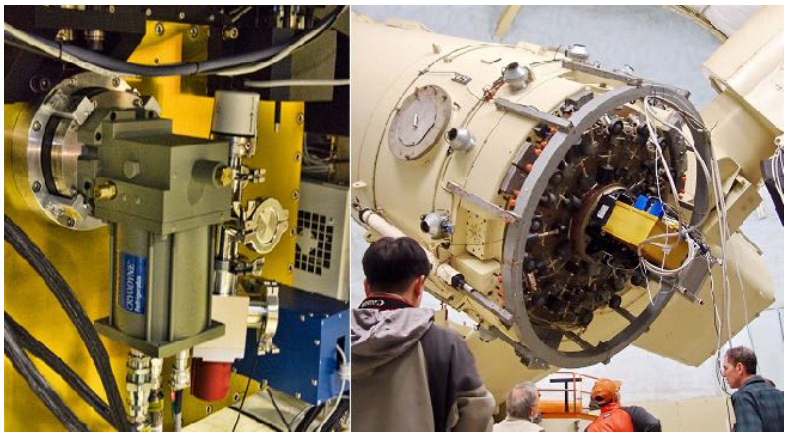


- M giants (3250 < T_{eff} < 4000 K) needed
- IGRINS spectrometer in H and K bands (1.5-1.7 & 2.0-2.3 μm) at R = 45 000 & *SNR > 100*
- **9** stars observed with IGRINS, only **7** with good SNR
- From McDonald Observatory!

New near-IR, stellar spectroscopic method

Govind Nadakumar's talk:

- Reliable stellar parameters for M giants of 3250 < T_{eff} < 4000 K
- Consistent and systematic, validated near-IR spectroscopic analysis of inner Milky Way *and close-by M giants* with same method and spectral lines
- Several nucleosynthetic channels: *α-, odd-Z, Fe-peak, neutron capture elements, and fluorine*



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

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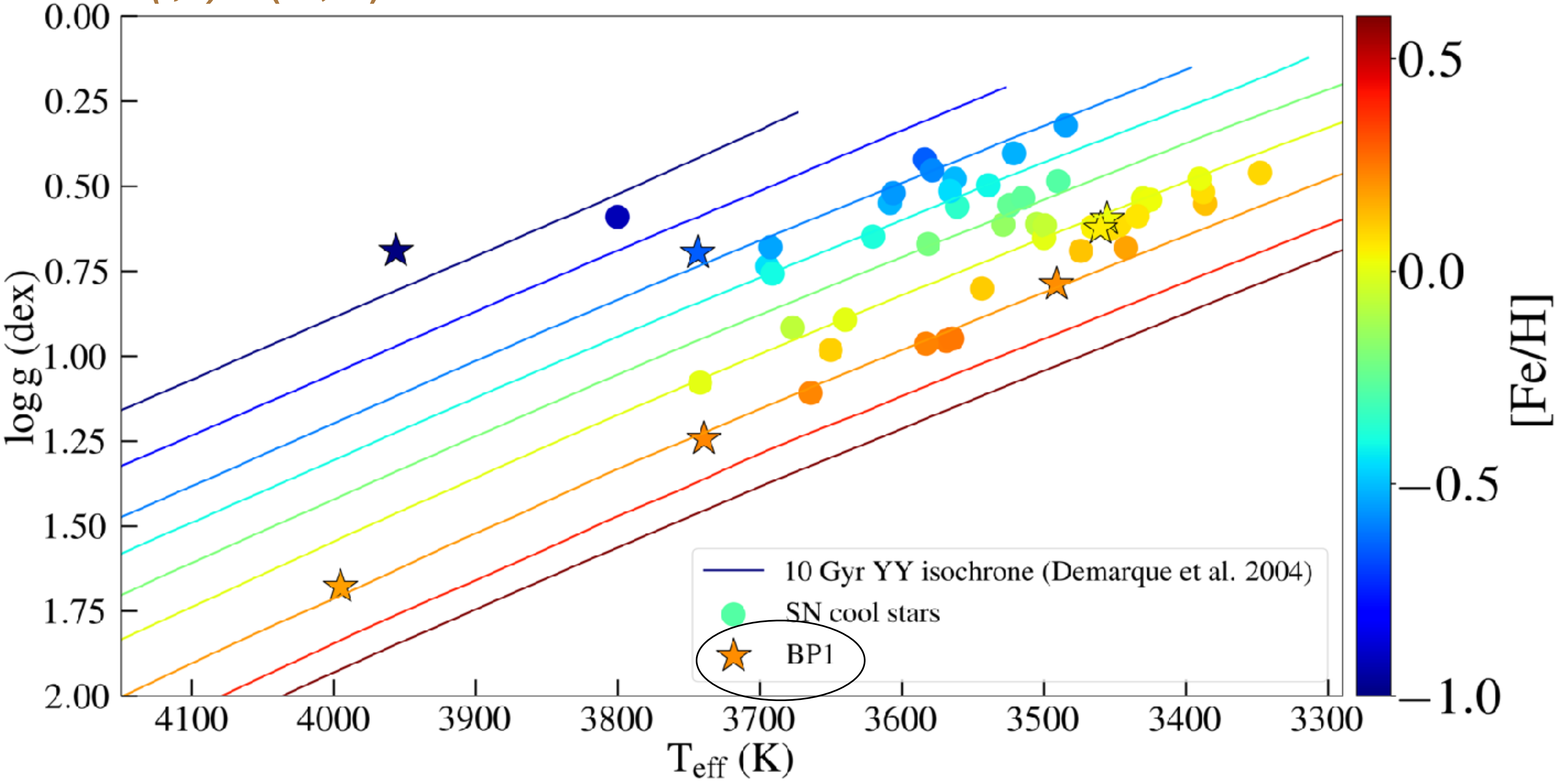

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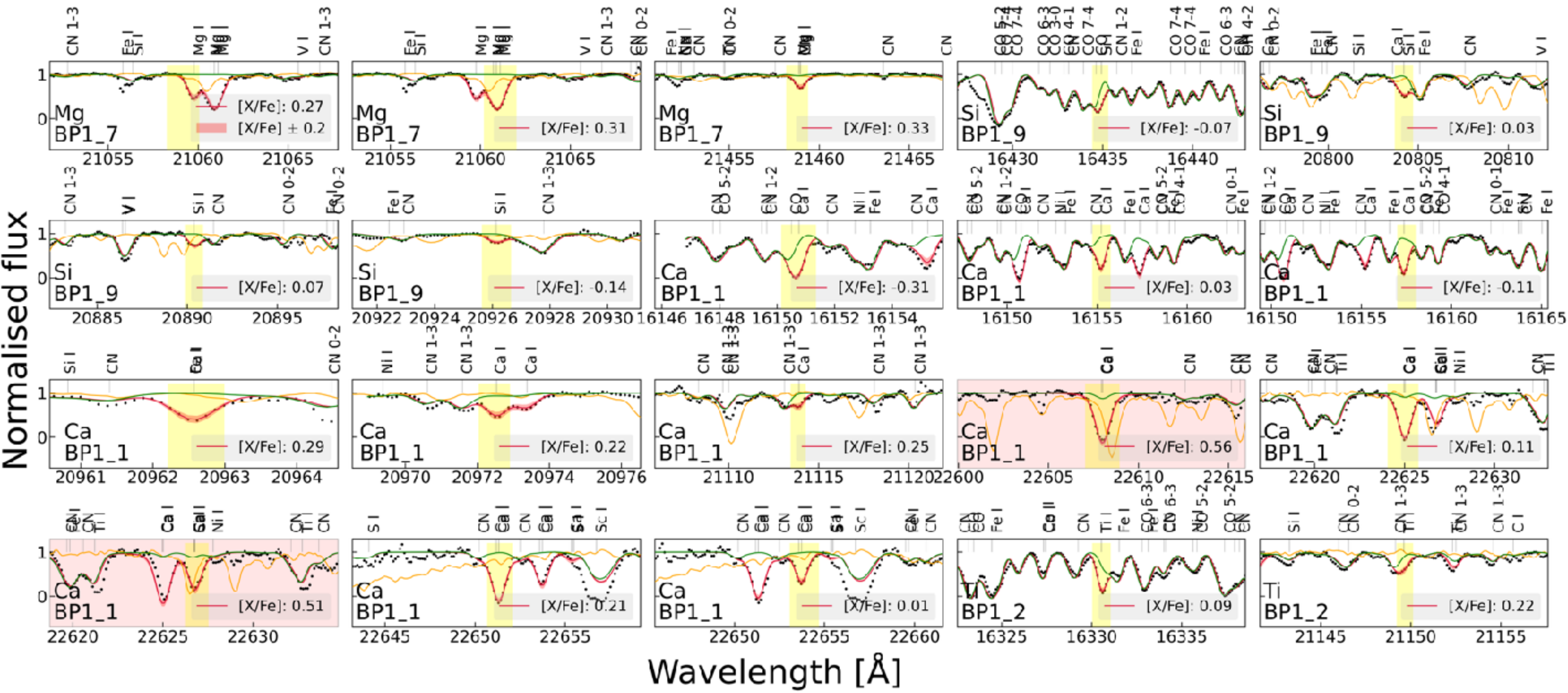

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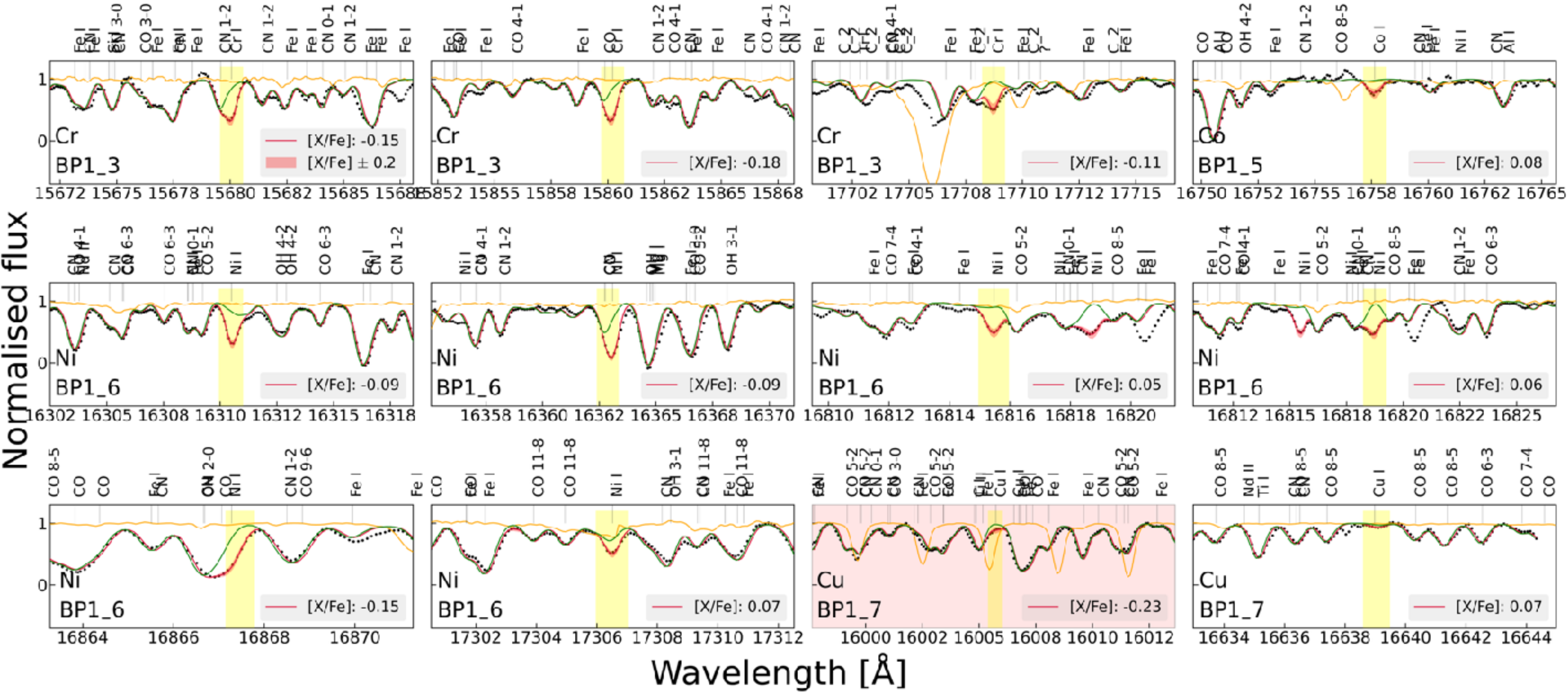

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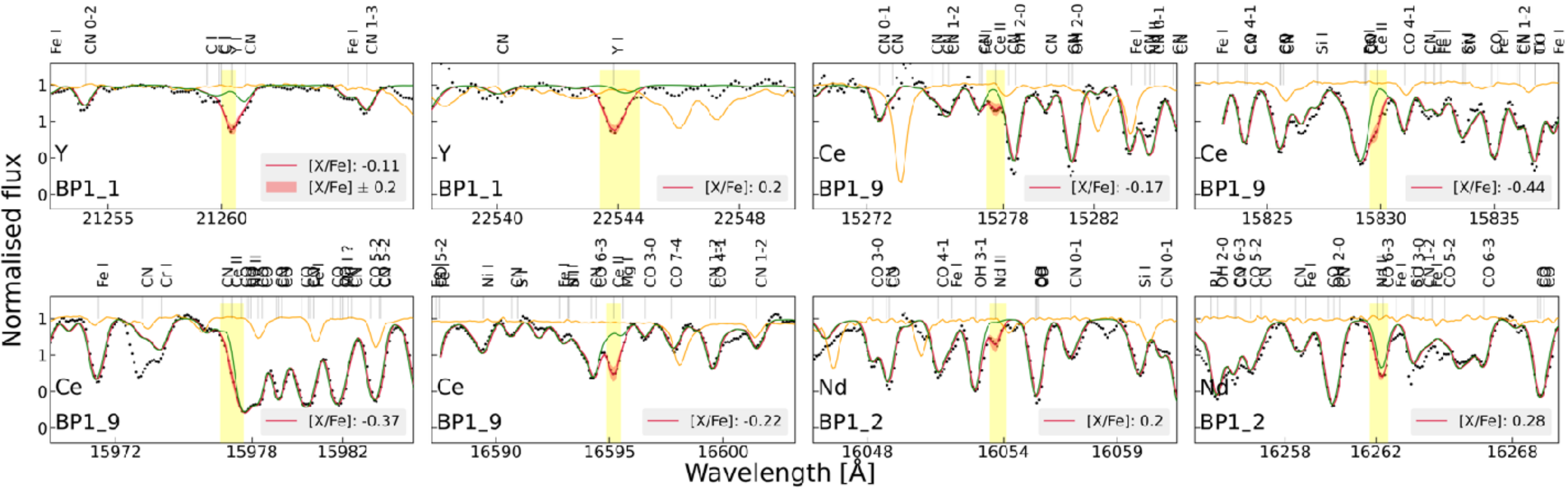
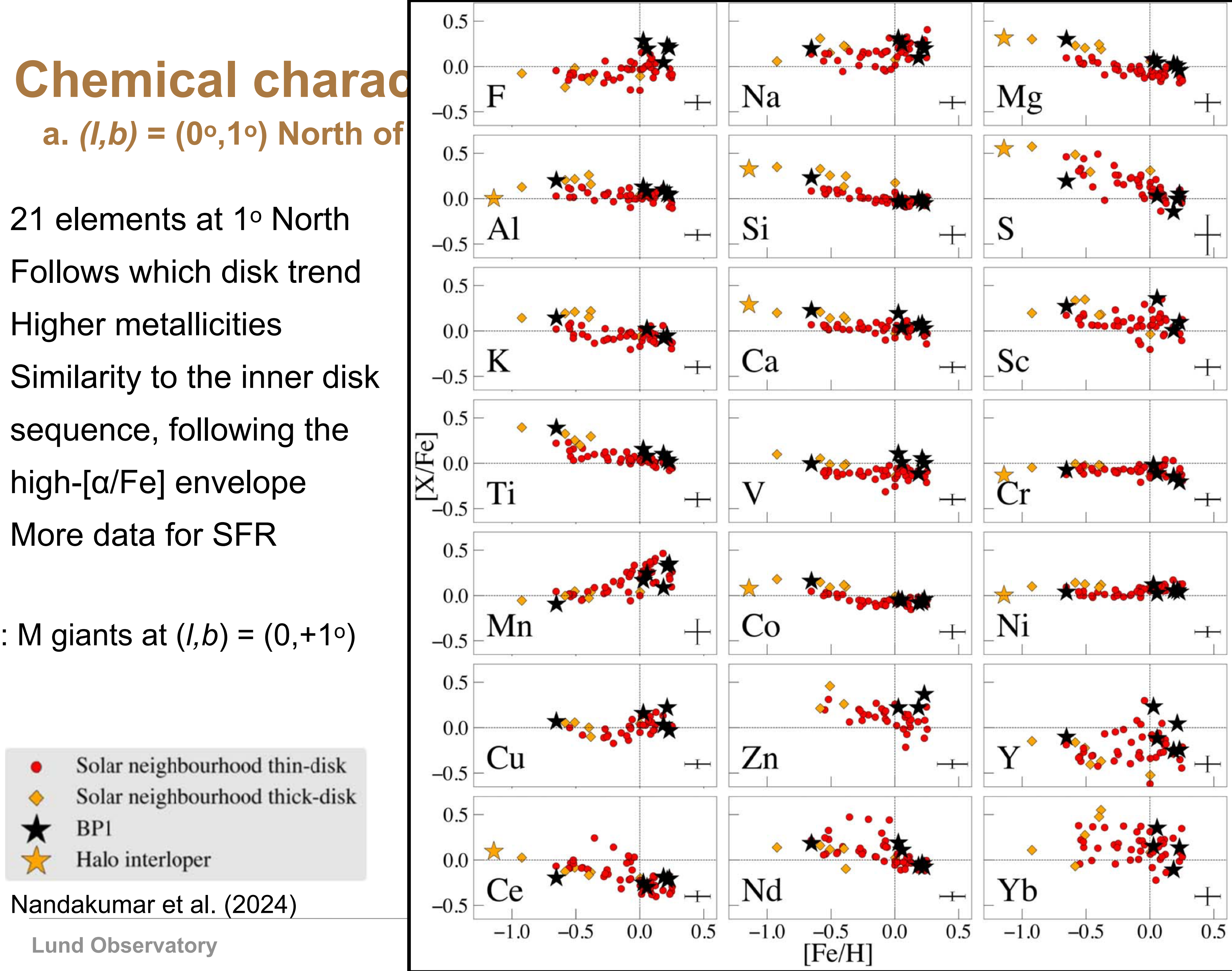


Chemical charac

a. *(l,b)* = (0°,1°) North of

- 21 elements at 1° North
- Follows which disk trend
- Higher metallicities
- Similarity to the inner disk sequence, following the high-[α/Fe] envelope
- More data for SFR

★: M giants at (*l*,*b*) = (0,+1°)



Nandakumar et al. (2024)

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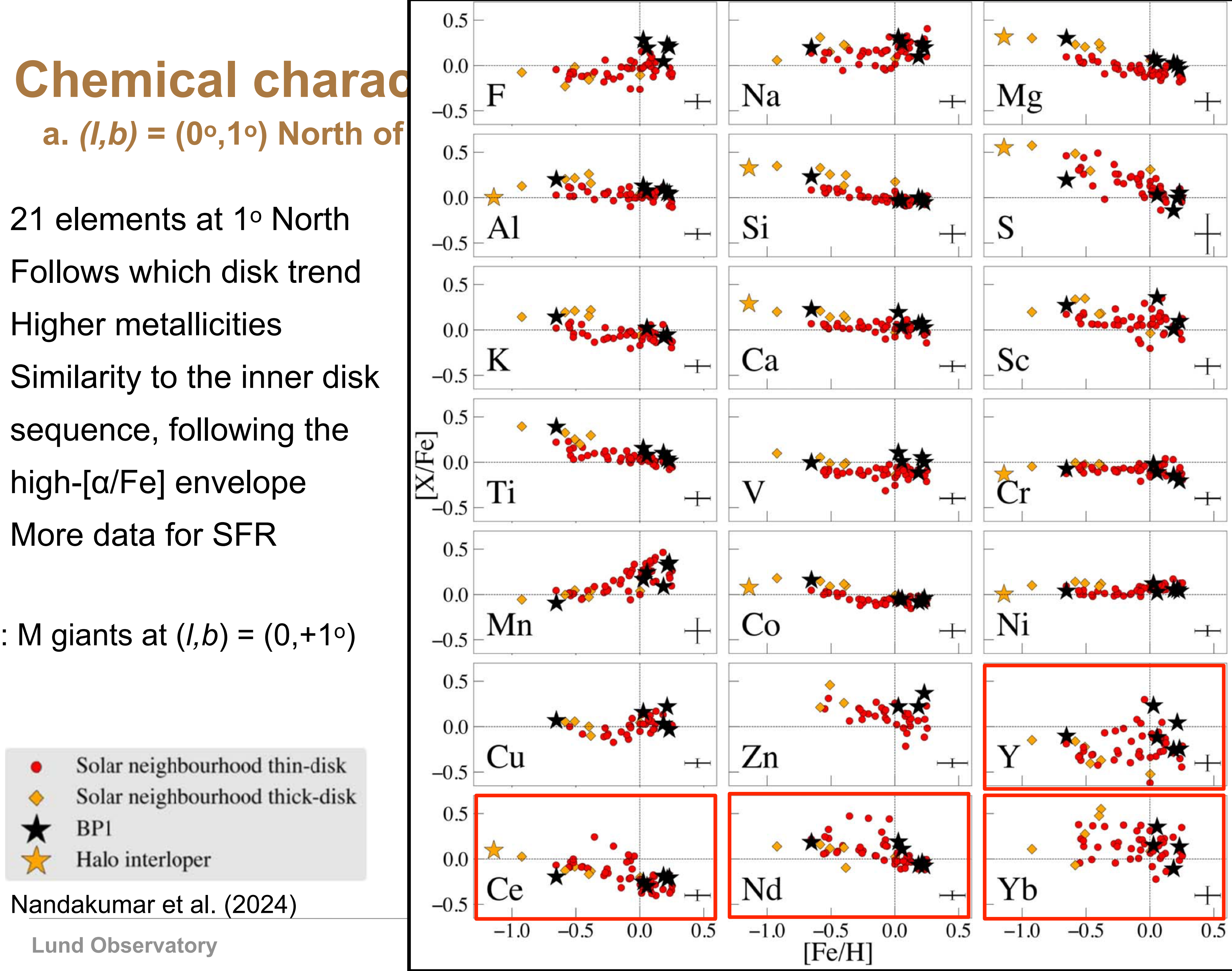

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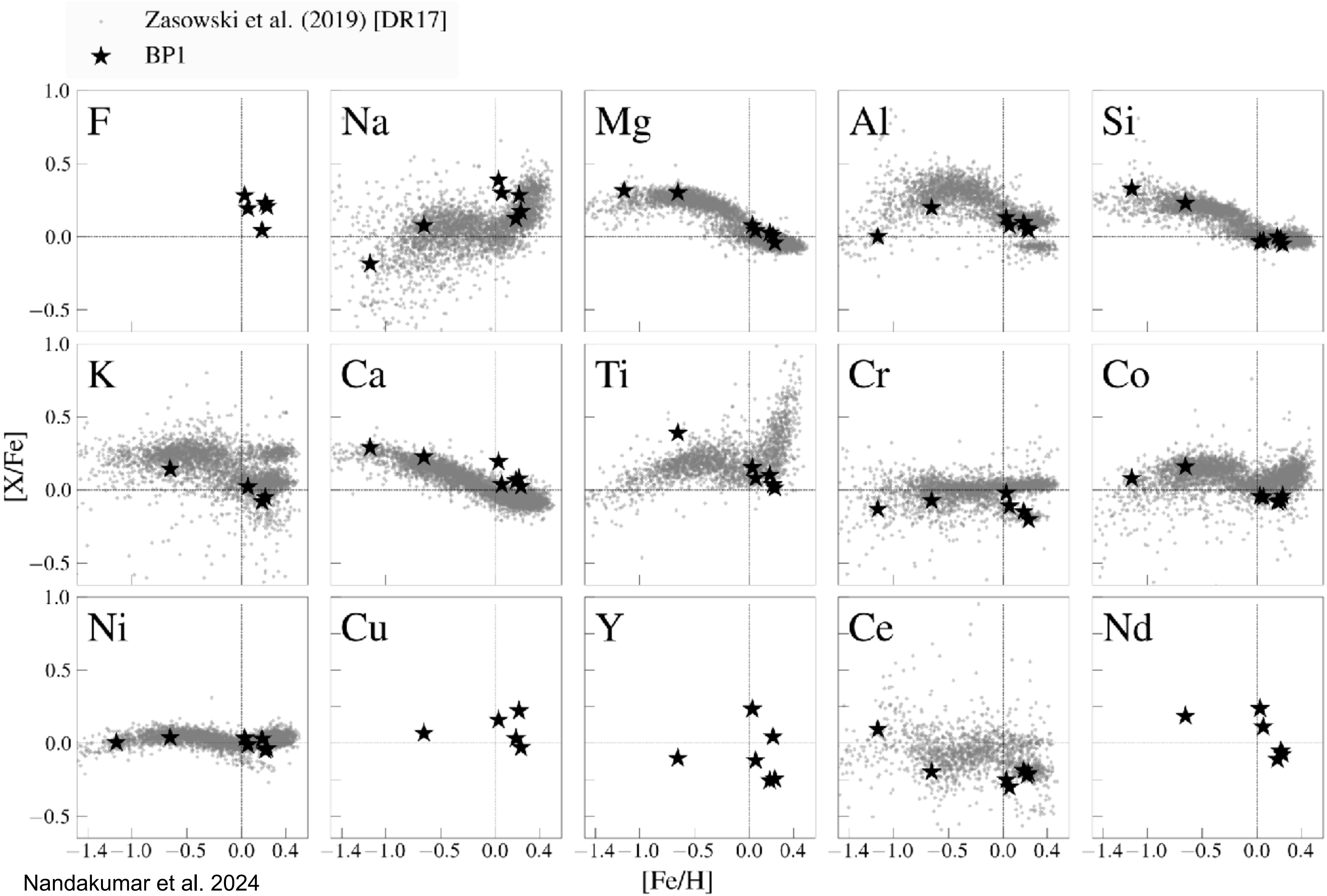

Nandakumar et al. 2024

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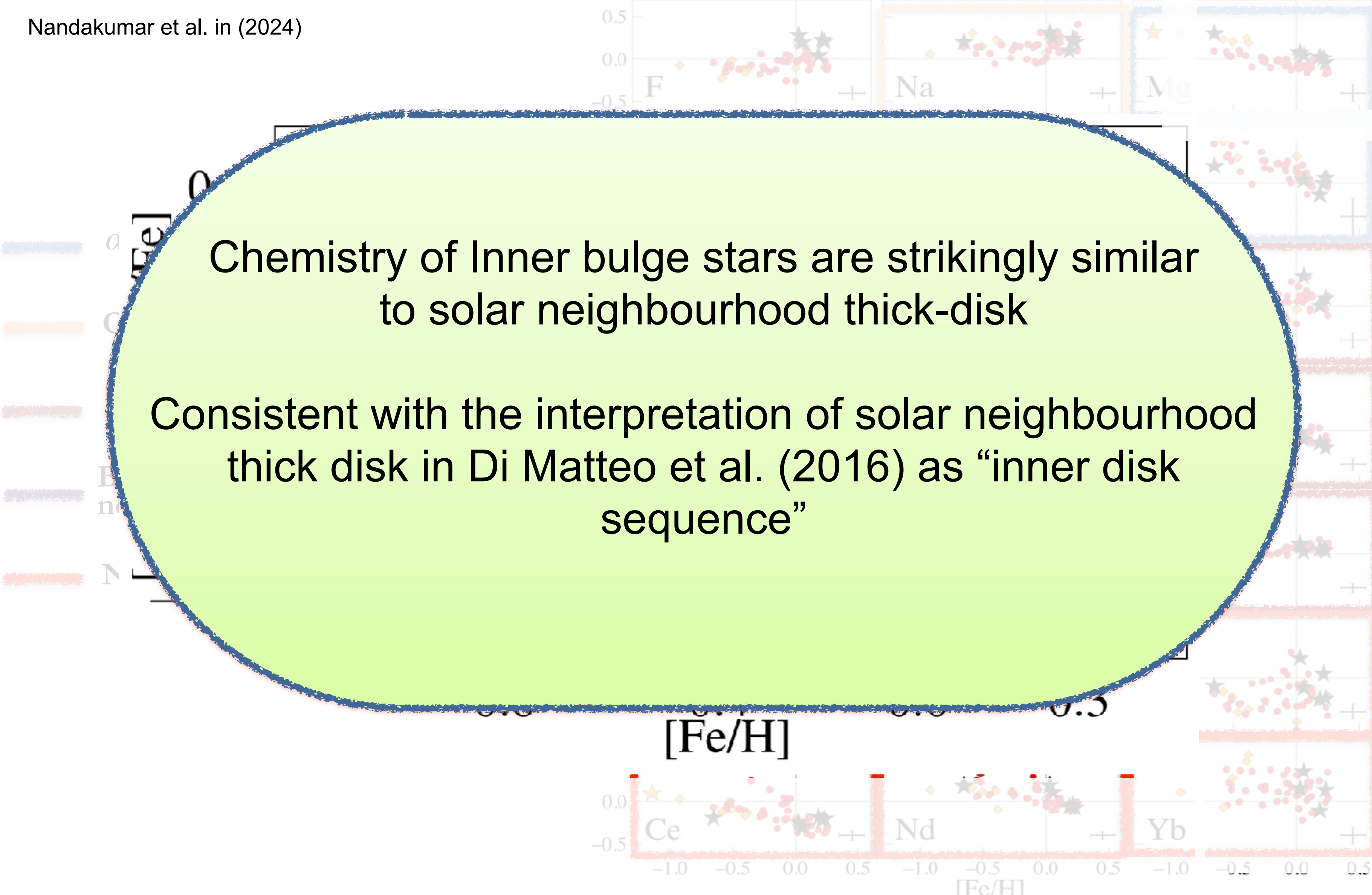
Nandakumar et al. in (2024)



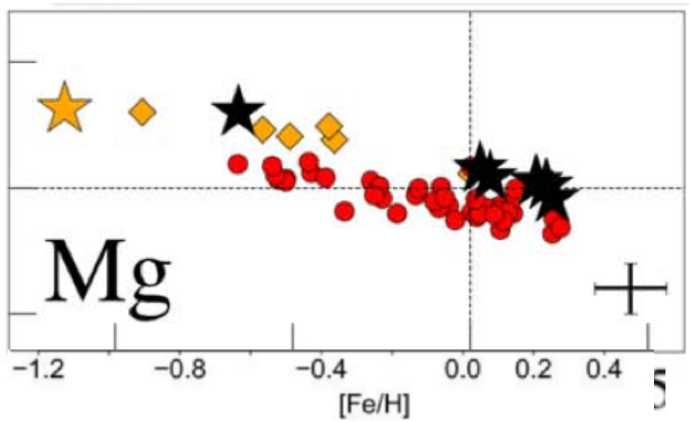
Chemistry of Inner bulge stars are strikingly similar to solar neighbourhood thick-disk

Consistent with the interpretation of solar neighbourhood thick disk in Di Matteo et al. (2016) as “inner disk sequence”

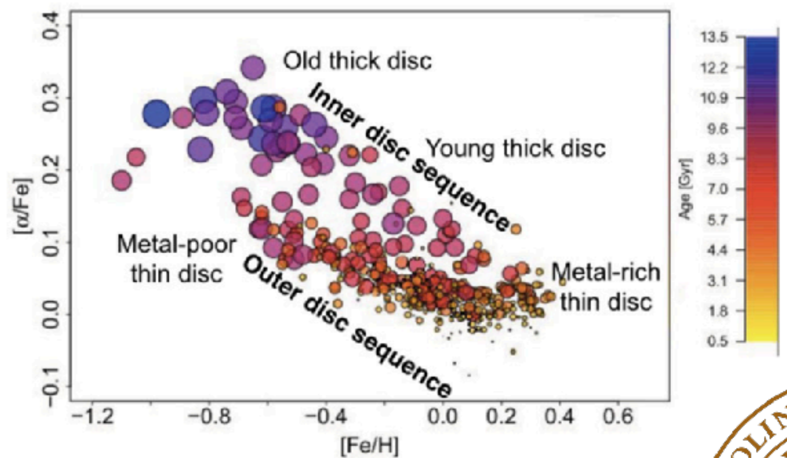
Chemical characterisation of the Galactic Center

a. *(l,b)* = (0°,1°) North of the Center

- Bulge similar to the thick disk, but extended to higher metallicity.
- This was also suggested by Di Matteo (2016), where the thick-disk (high-α) population is referred to as “inner disk sequence” including the metal-rich thin-disk population. This is considered to be the same structure as the thick-disk or “inner disk sequence” (see also Haywood et al. 2013).
- cf. simulation VINTERGATAN (Agertz et al. 2021; Renaud et al. 2021).



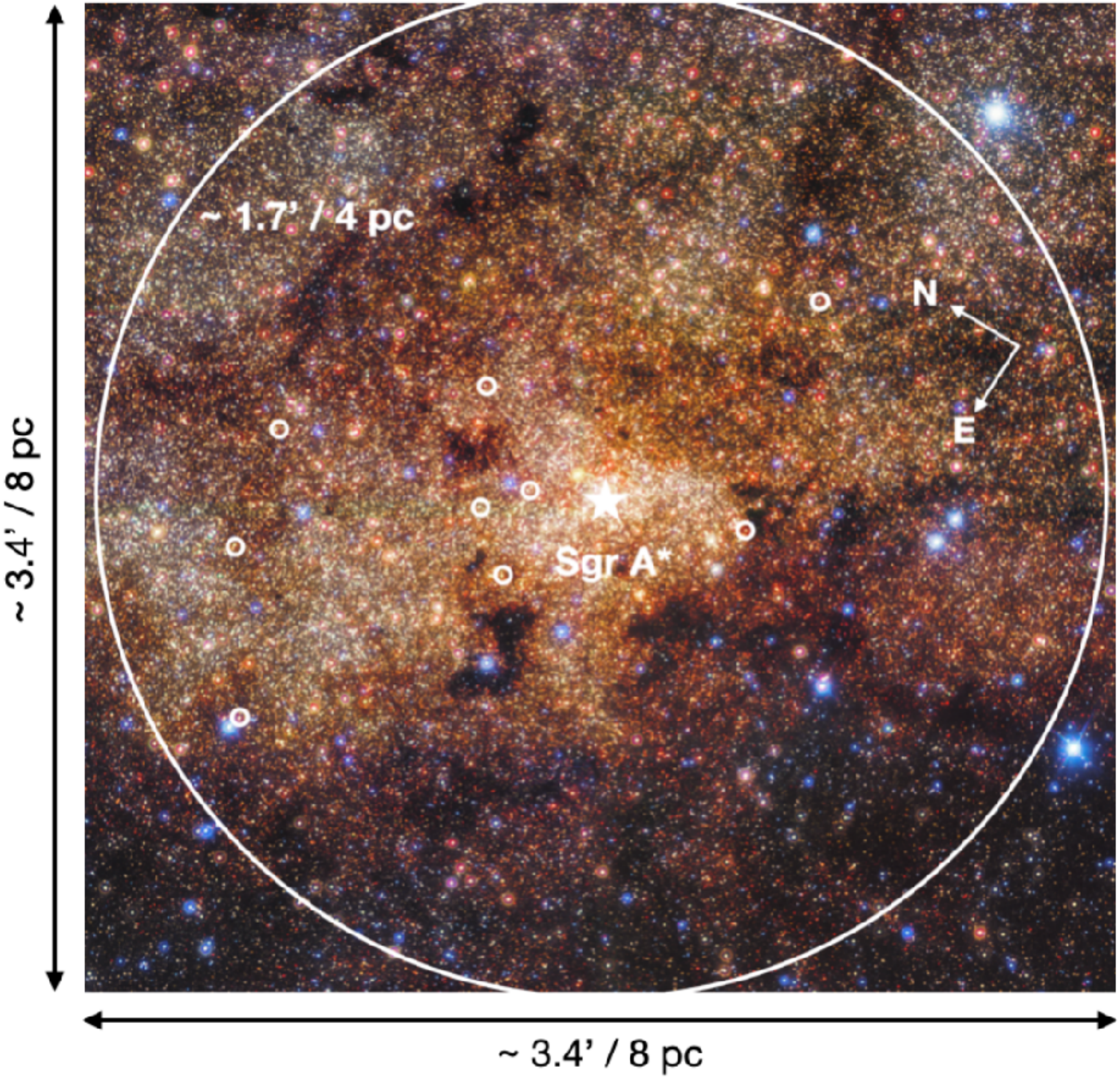
Nandakumar et al. (2024)



Di Matteo (2016)

Chemical characterisation of the Galactic Center

b. *Nuclear Star Cluster* (Ryde et al. 2025 & Nadakumar et al. 2025)



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17:45:41.016	-29:00:15.134	10.39	2023-04-04
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17:45:46.187	-28:59:48.253	10.17	2023-03-24
17:45:42.751	-29:00:38.617	10.84	2023-04-28
17:45:42.012	-29:00:43.870	10.85	2023-04-30
17:45:40.671	-29:00:15.318	10.74	2022-05-16
17:45:41.016	-29:00:04.766	10.28	2023-04-05
17:45:42.000	-29:00:20.000	10.50	2023-04-26
17:45:39.400	-29:00:58.900	10.60	2023-04-28
17:45:41.900	-28:59:23.390	10.49	2023-03-24
17:45:43.900	-28:59:28.500	10.70	2023-04-26
17:45:40.930	-29:00:24.390	10.44	2023-04-04
17:45:42.90	-29:00:09.60	10.90	2024-03-31
17:45:40.474	-29:00:13.450	11.06	2024-03-31
17:45:39.59	-28:59:56.21	10.82	2024-04-11
17:45:35.64	-29:00:47.00	10.75	2024-04-20

Chemical characterisation of the Galactic Center

b. *Nuclear Star Cluster*

- We are analysing 20 M giants in the NSC with good SNR observed in 2023 & 2024 with IGRINS at Gemini S

- Detailed Mg, Si, and Ca (Ryde et al. 2025)

- Analysed with same pipeline on very similar quality spectra

- 23 elemental trends in the NSC: alpha, Fe-peak, Na, r- and s-elements (Nandakumar et al. 2025)

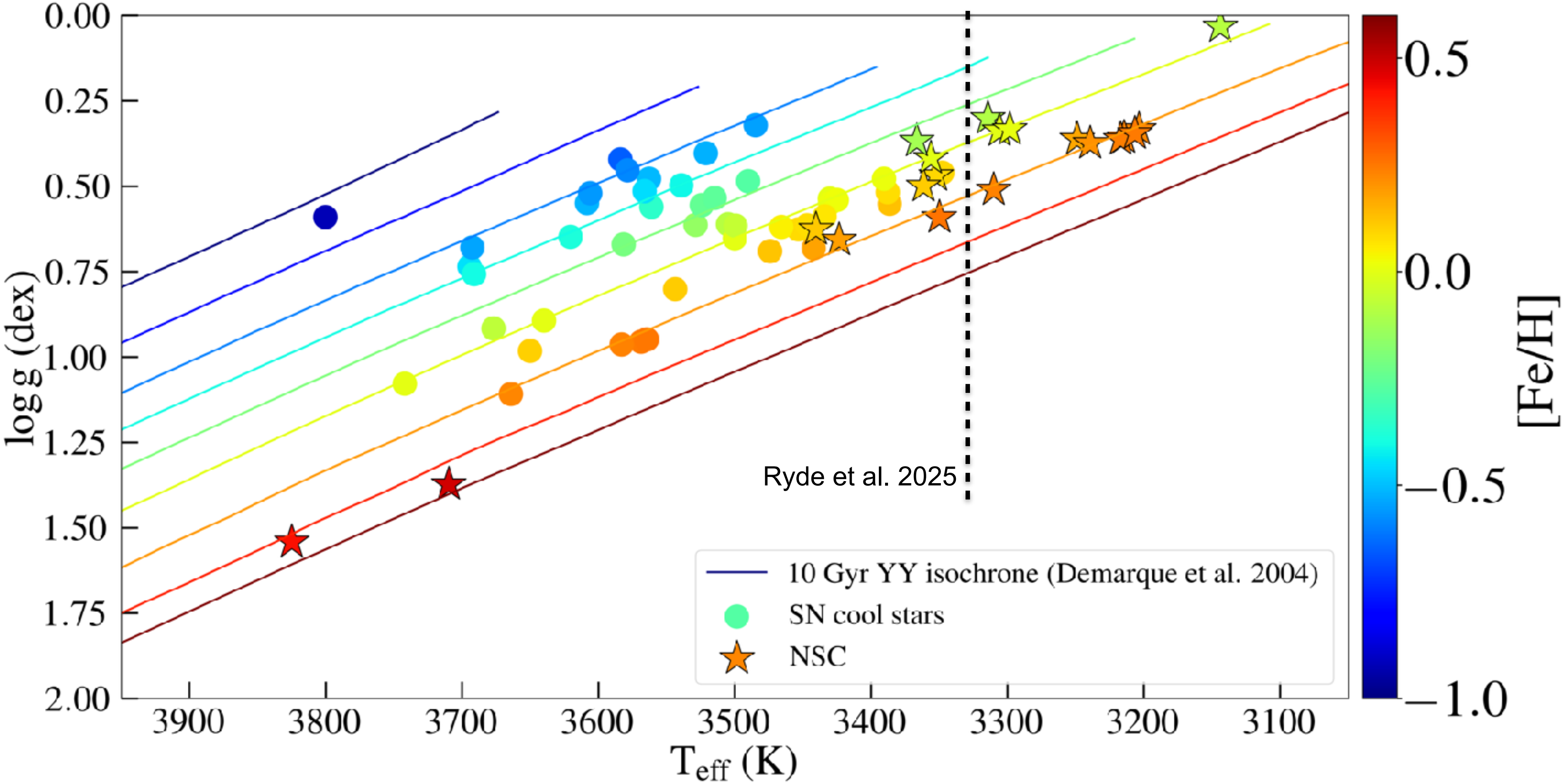
- Applying for more Gemini/IGRINS and Keck/NIRSPEC time of Galactic Center: NSC, NSD, inner bulge

Table 1: Observational details of M giant stars.

Name	RA h:m:s	DEC d:m:s	K (mag)	Date UT
COOL16611	17:45:43.200	-28:59:41.400	10.10	2022-05-10
COOL7137	17:45:38.100	-29:00:58.070	10.50	2023-04-28
COOL7191	17:45:37.900	-29:00:57.600	10.50	2023-04-28
FK137	17:45:41.360	-29:00:13.025	10.99	2023-04-29
FK14	17:45:41.016	-29:00:15.134	10.39	2023-04-04
FK48	17:45:41.301	-29:00:08.406	10.69	2023-04-30
FK5020265	17:45:46.187	-28:59:48.253	10.17	2023-03-24
FK6020735	17:45:42.751	-29:00:38.617	10.84	2023-04-28
FK6020974	17:45:42.012	-29:00:43.870	10.85	2023-04-30
FK87	17:45:40.671	-29:00:15.318	10.74	2022-05-16
FK94	17:45:41.016	-29:00:04.766	10.28	2023-04-05
Feld31	17:45:42.000	-29:00:20.000	10.50	2023-04-26
Feld84	17:45:39.400	-29:00:58.900	10.60	2023-04-28
GC15540	17:45:41.900	-28:59:23.390	10.49	2023-03-24
GC16890	17:45:43.900	-28:59:28.500	10.70	2023-04-26
GC25a	17:45:40.930	-29:00:24.390	10.44	2023-04-04
GC11532	17:45:42.90	-29:00:09.60	10.90	2024-03-31
FK152	17:45:40.474	-29:00:13.450	11.06	2024-03-31
GC13727	17:45:39.59	-28:59:56.21	10.82	2024-04-11
GC16895	17:45:35.64	-29:00:47.00	10.75	2024-04-20

Chemical characterisation of the Galactic Center

b. *Nuclear Star Cluster*



Chemical characterisation of the Galactic Center

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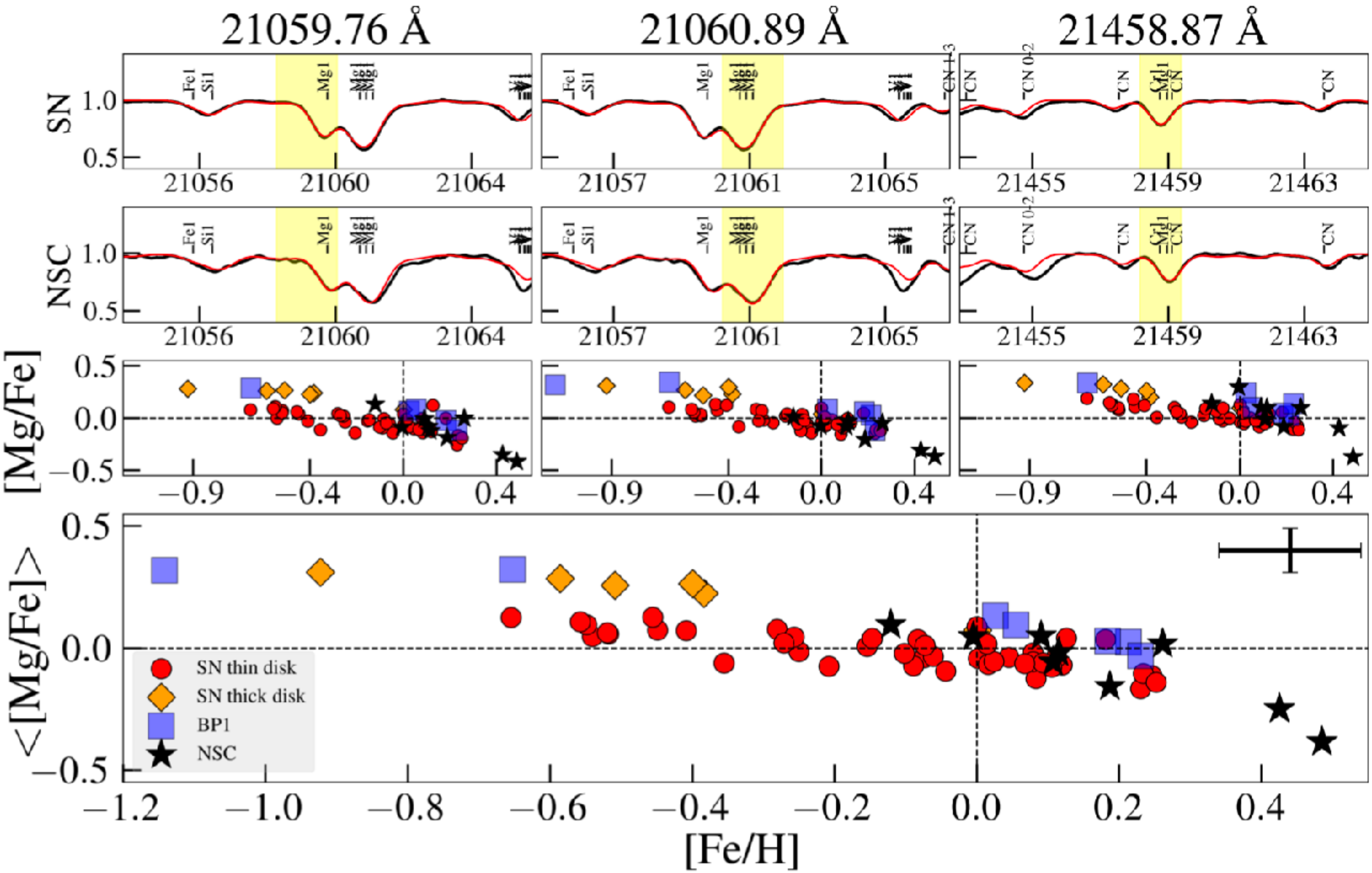

Ryde et al. 2025

Chemical characterisation of the Galactic Center

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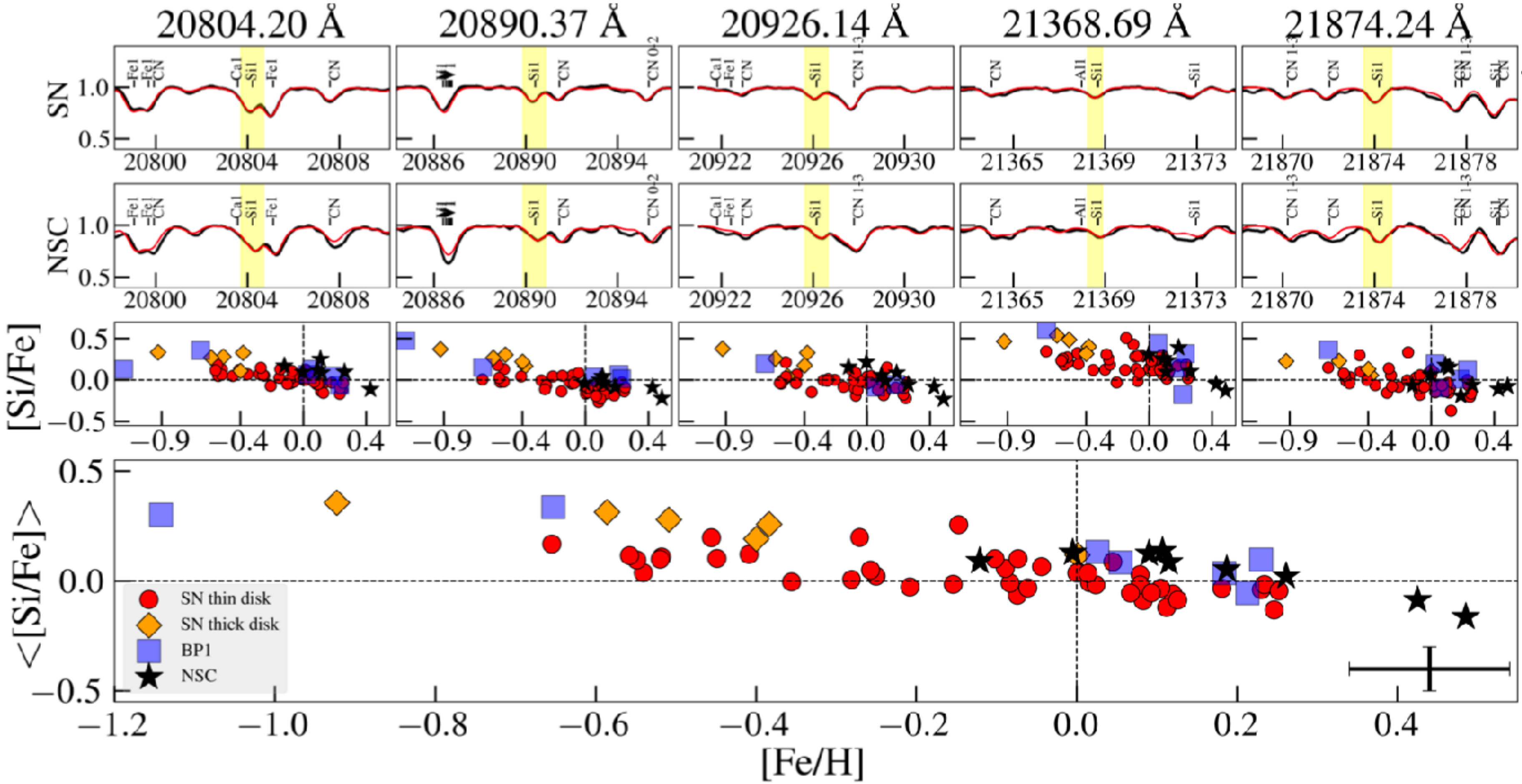

Ryde et al. 2025

Chemical characterisation of the Galactic Center

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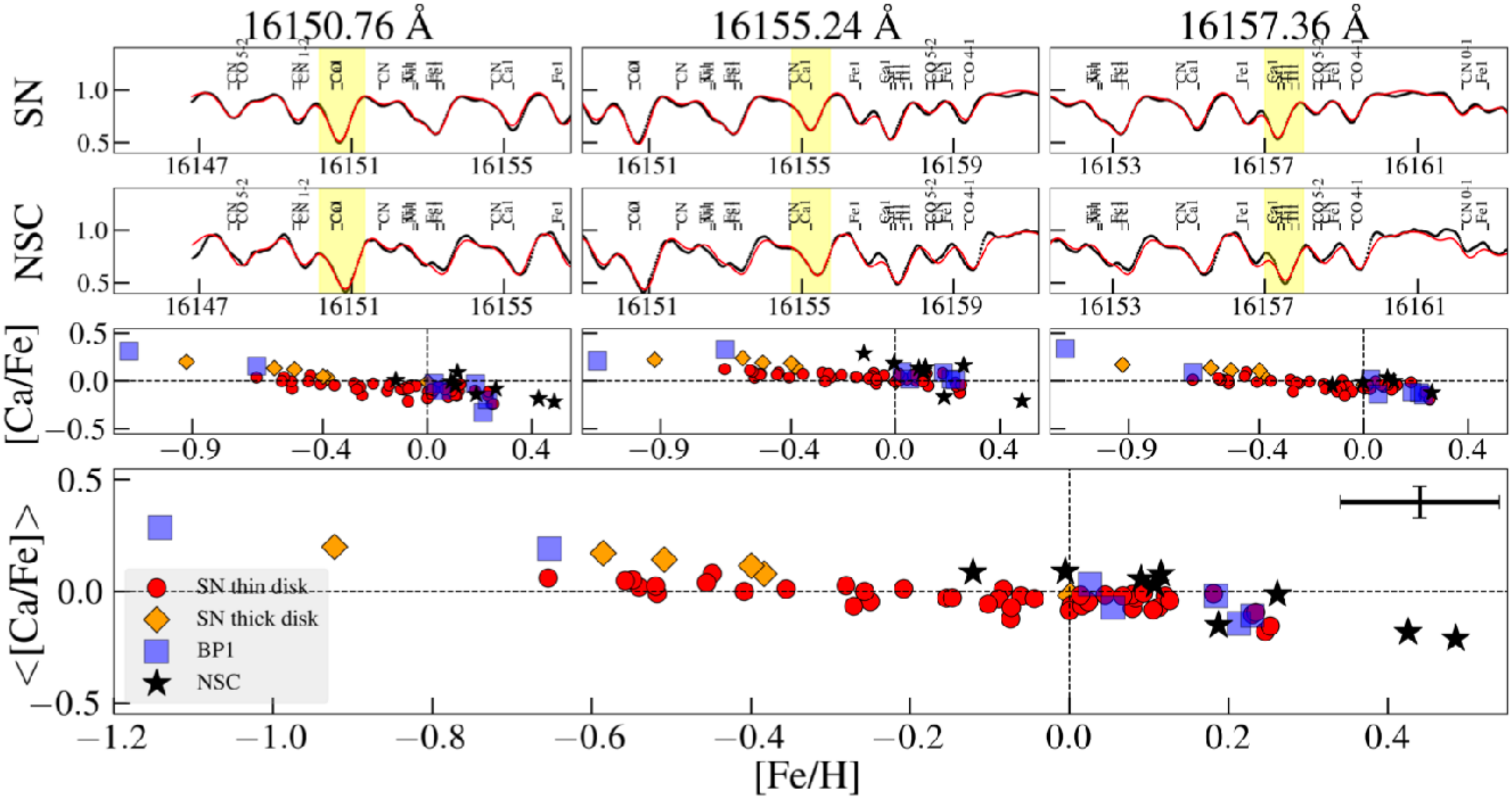

Ryde et al. 2025

Chemical characterisation of the Galactic Center

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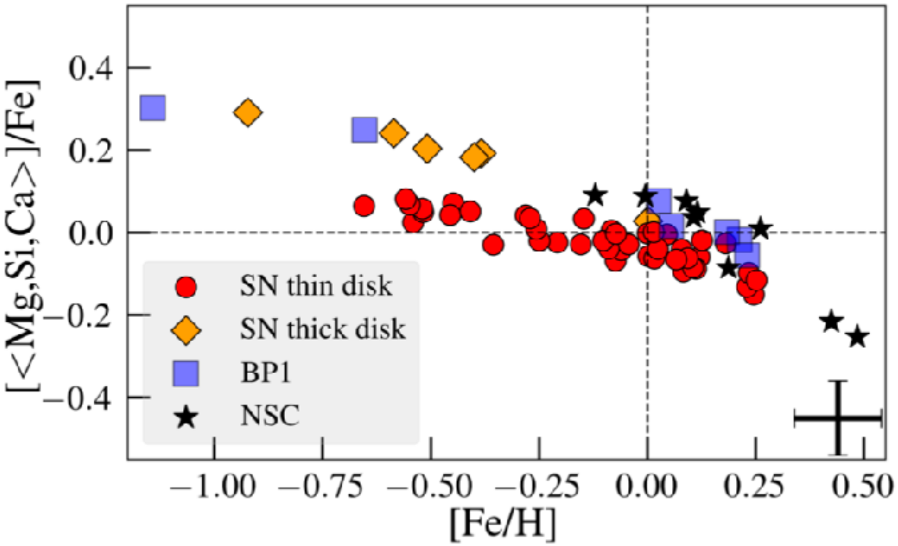

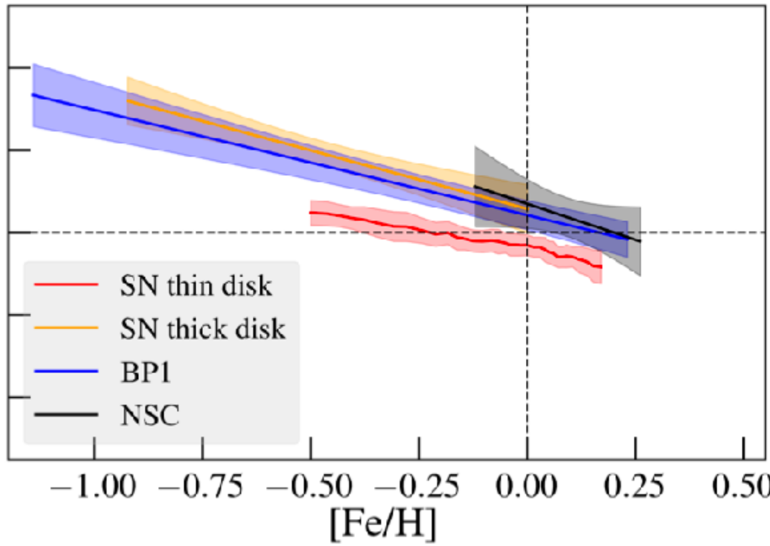

Ryde et al. 2025

- NSC alphas enhanced following inner-disk sequence
- Similar to stars +1° North of Center
- NSC population likely shares a similar evolutionary history with the inner bulge, challenging a recent dominant star-formation burst
- NSC SFH and that of the thick disk at the same metallicities, must also have been similar

Chemical characterisation of the Galactic Center

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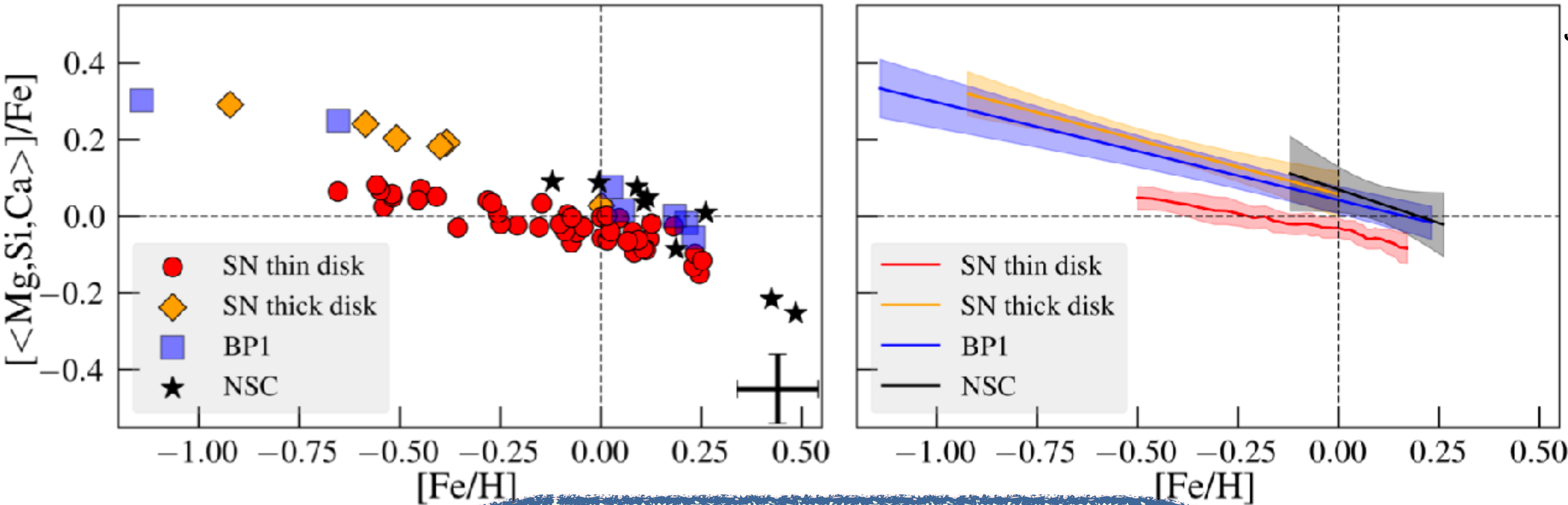

Ryde et al. 2025

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

Conclusions

- To understand Galactic Center need detail abundances at high precision and accuracy. Differential SN sample key.
- Largest set of abundance of the NSD and NSC yet
- 23 elements now possible to retrieve from high-res near-IR spectra
- (l,b)=(0,1^{o}): similar thick disk extension trends, with hint of larger SFR
- Ba is now possible, and also s/r-element Yb.
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Observatoire de la CÔTE d'AZUR

Wenner-Gren Foundations
Wenner-Gren Stiftelserna

Neutron-capture elements in the near-IR

s- and r-elements available in H- and K-band spectra

- Few neutron capture elements in the near-IR identified
- *Cu, Ce, Nd* (H band) and *Y* (K band) have been used before

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- Few neutron capture elements in the near-IR identified
- *Cu, Ce, Nd* (H band) and *Y* (K band) have been used before
- r/s element *Yb* (Montelius et al. 2022)
- Identification and characterization of a line at 2.33 µm from the s-element *Ba* (Nandakumar et al. 2024)

Neutron-capture elements in the near-IR

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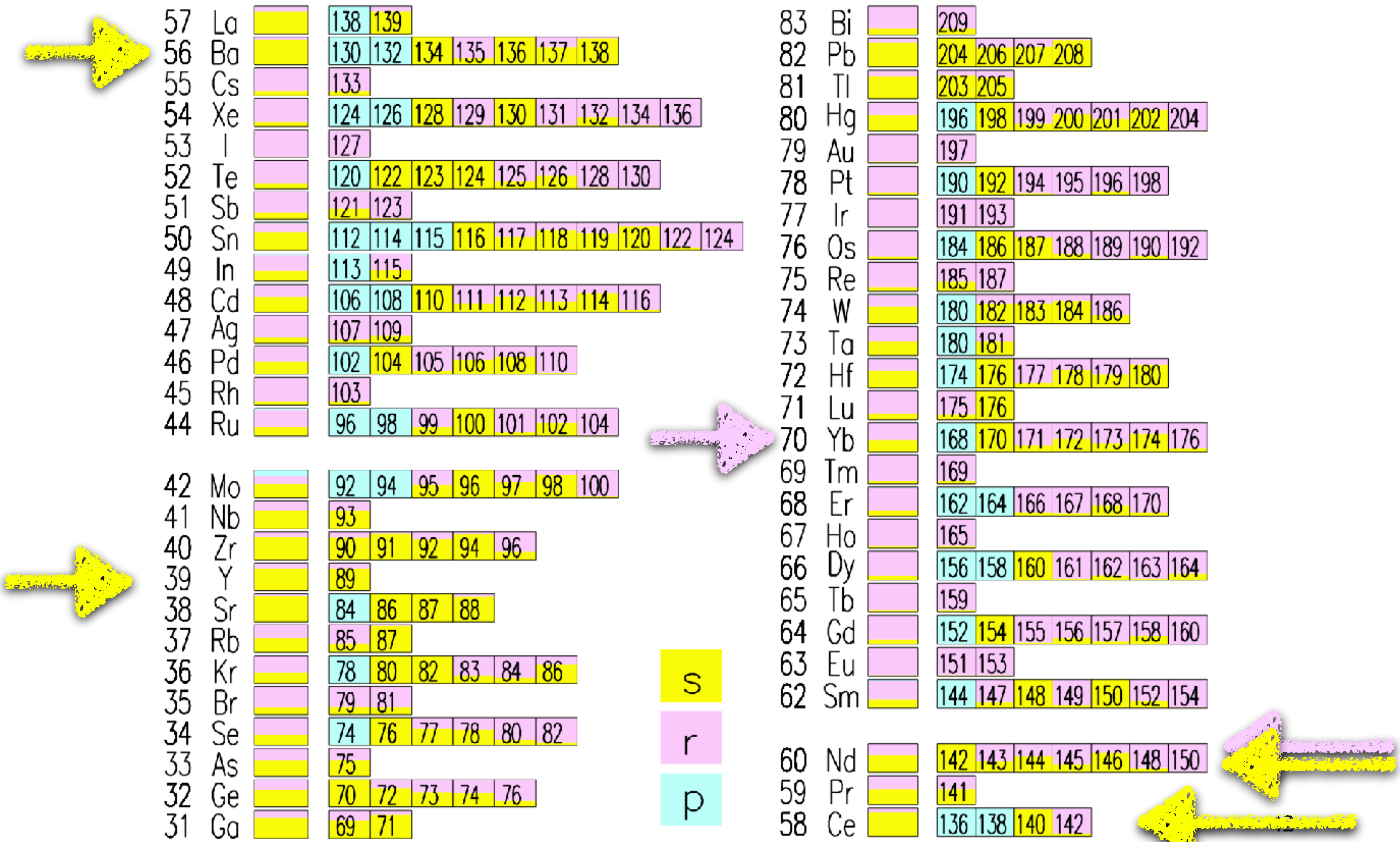
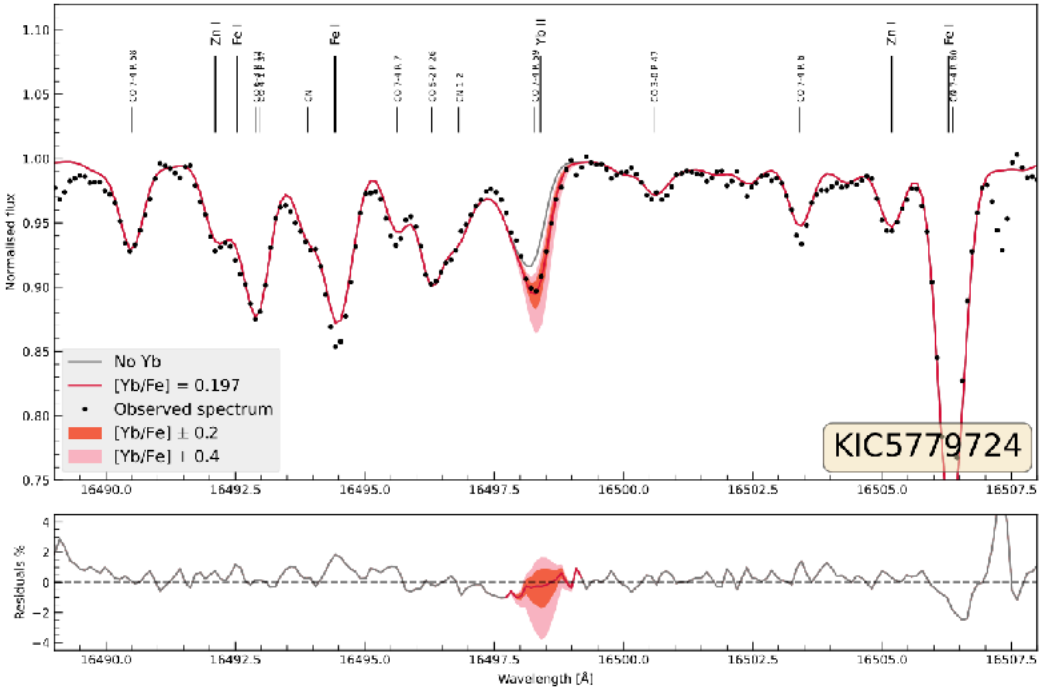


Prantzos et al. 2018

Neutron-capture elements in the near-IR

Ytterbium in the Galactic disk

We find that Yb is possible to retrieve, but only in high-res, H-band spectra (e.g. IGRINS but not APOGEE).



Montelius et al. A&A 665, A135 (2022)

- M giants of 3100< T_{eff} < 4000 K
- IGRINS spectrometer on Gemini S
- *R = 45000*
- H and K bands (1.5 – 1.75 and 2.05 – 2.3 µm),
- *SNR > 100*

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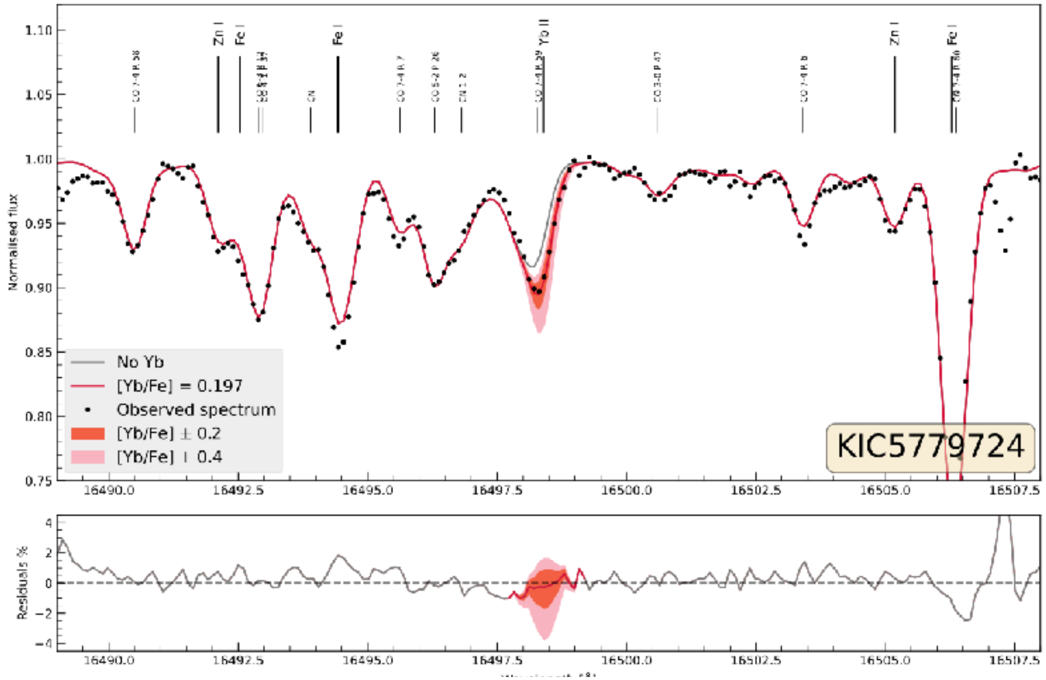

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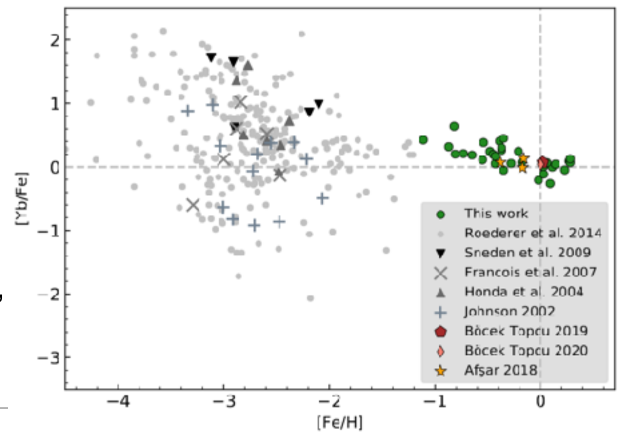
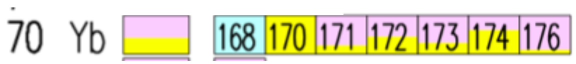


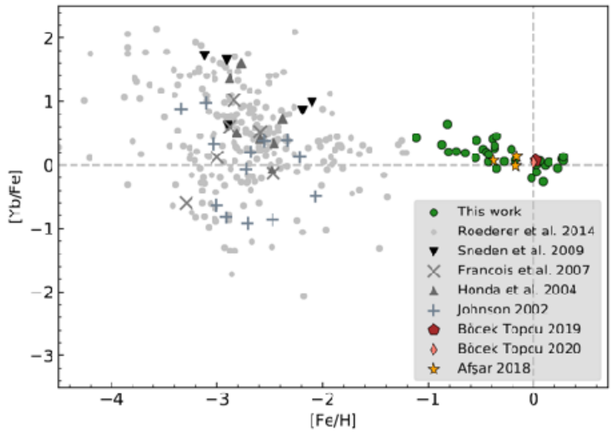
Neutron-capture elements in the near-IR

Ytterbium in the Galactic disk

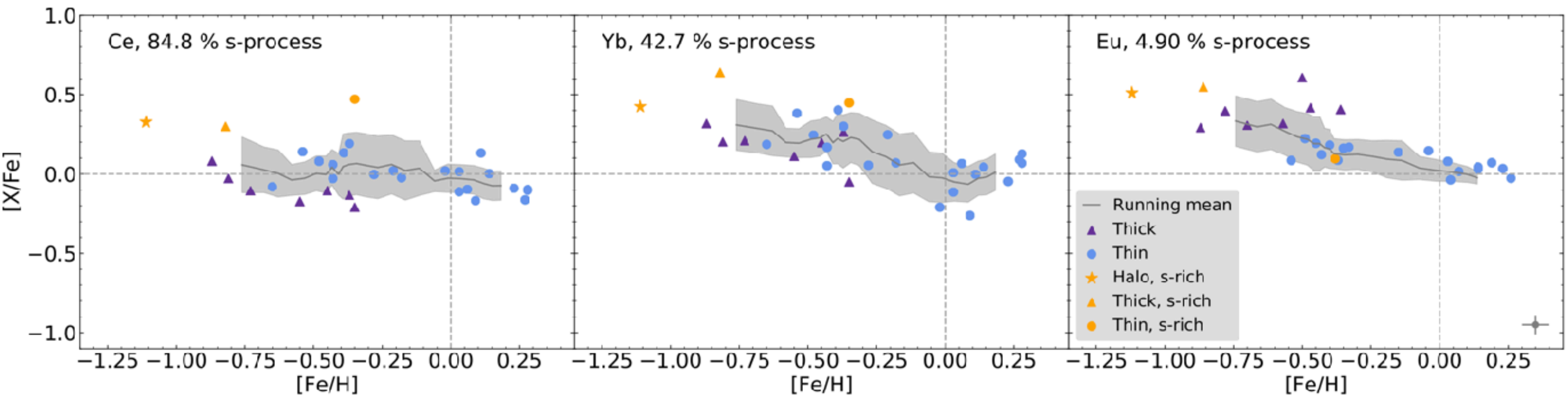
- Difficulties due to blending CO lines
- 40 % s-process and 60 % r-process (Bisterzo et al. 2014, Prantzos et al. 2020)



- Can compare with Ce (s) and Eu (r) from Forsberg et al. 2019

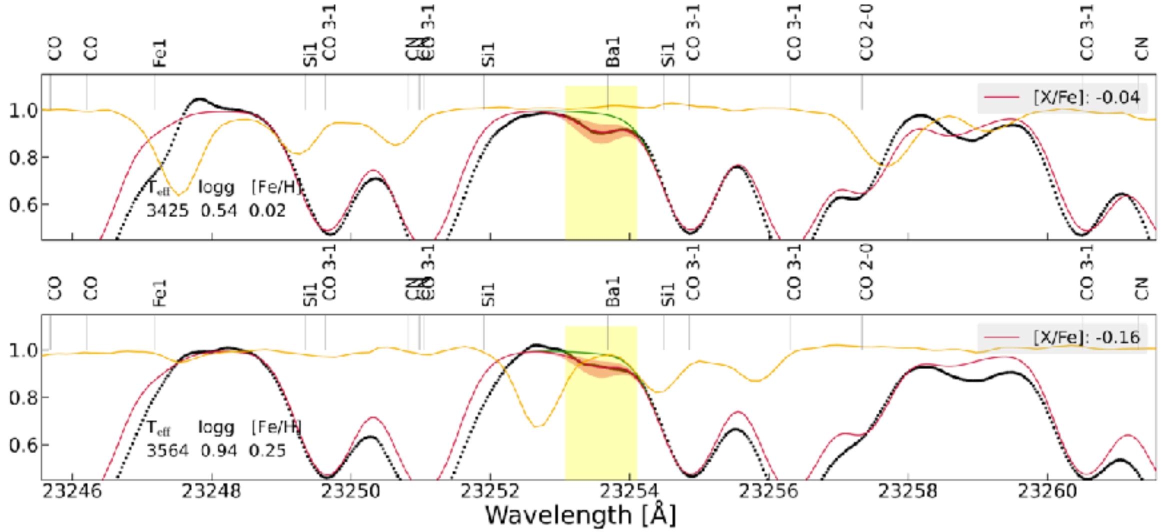


Montelius et al. 2022

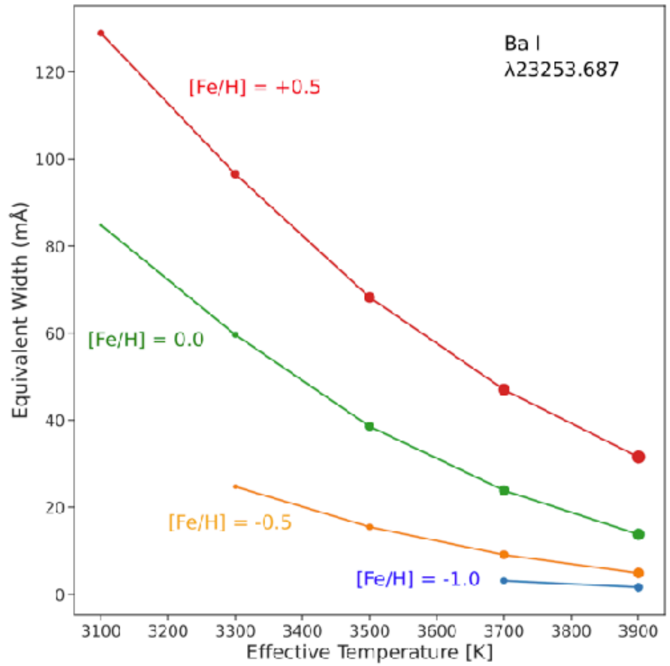


Neutron-capture elements in the near-IR

Barium in the Galactic disk



- Ba I line (6s5d $^3D_2 \rightarrow$ 6s6p $^3P_2^o$)
- 23 253.5 Å
- 37 M giants observed with IGRINS



Nandakumar et al., A&A, 2024

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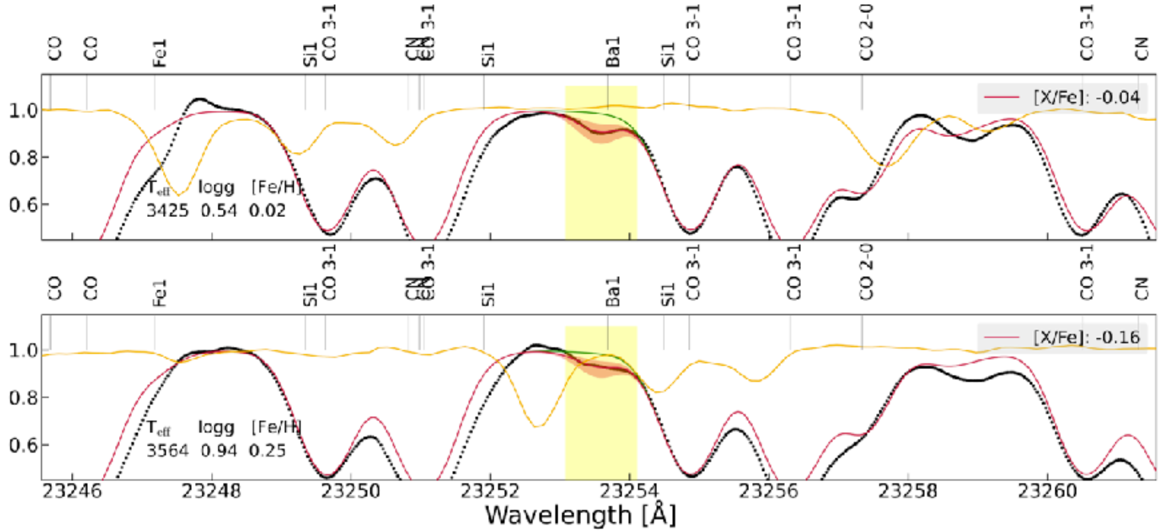

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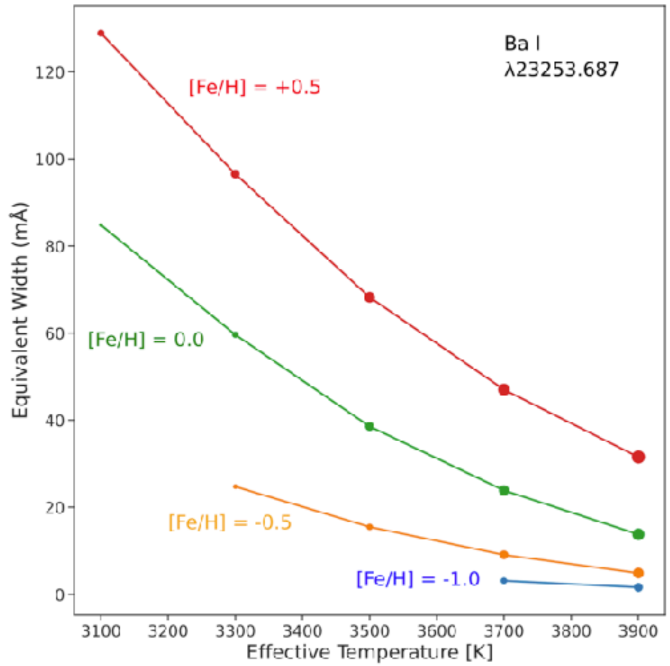

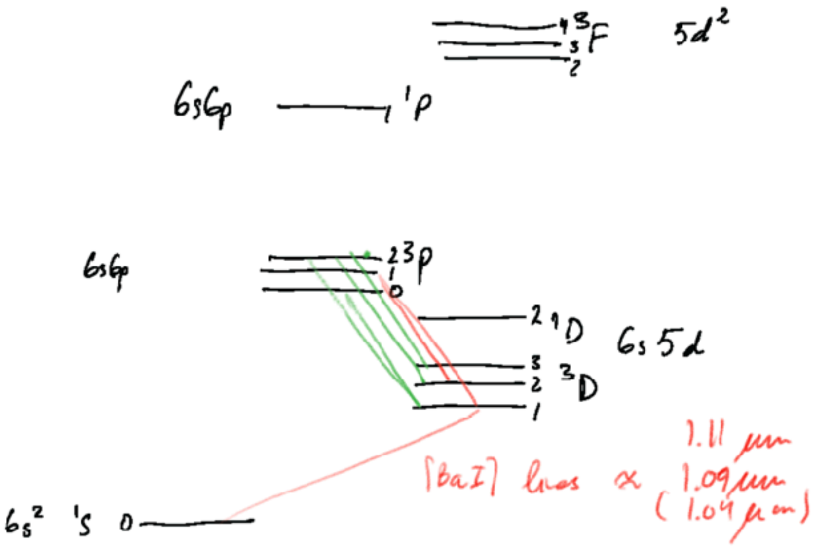

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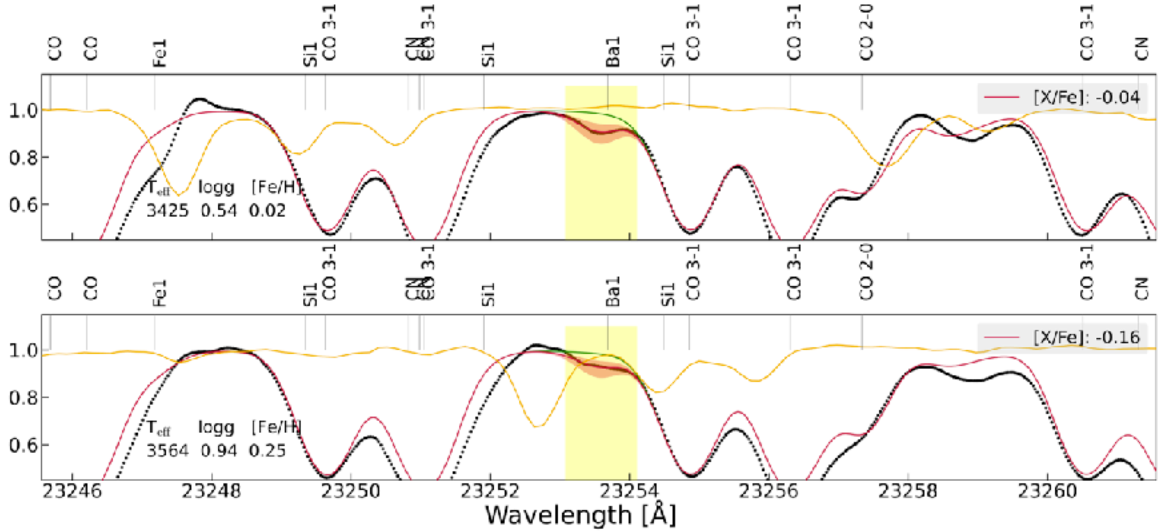

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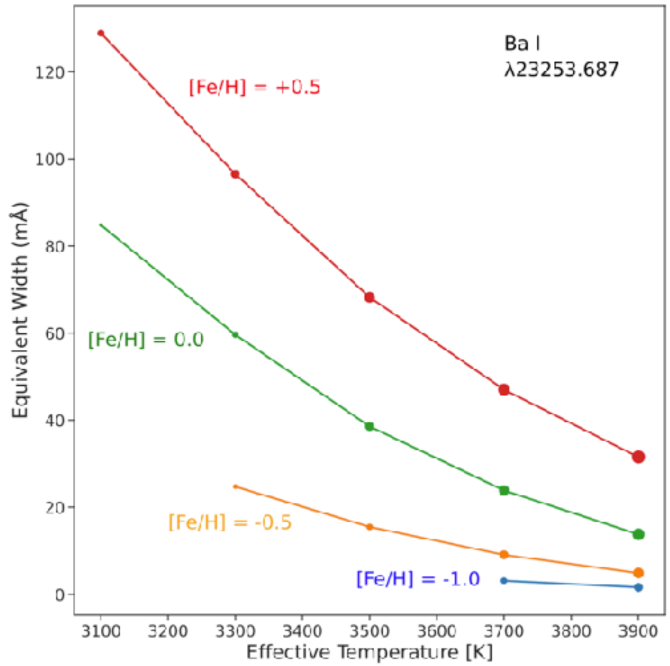

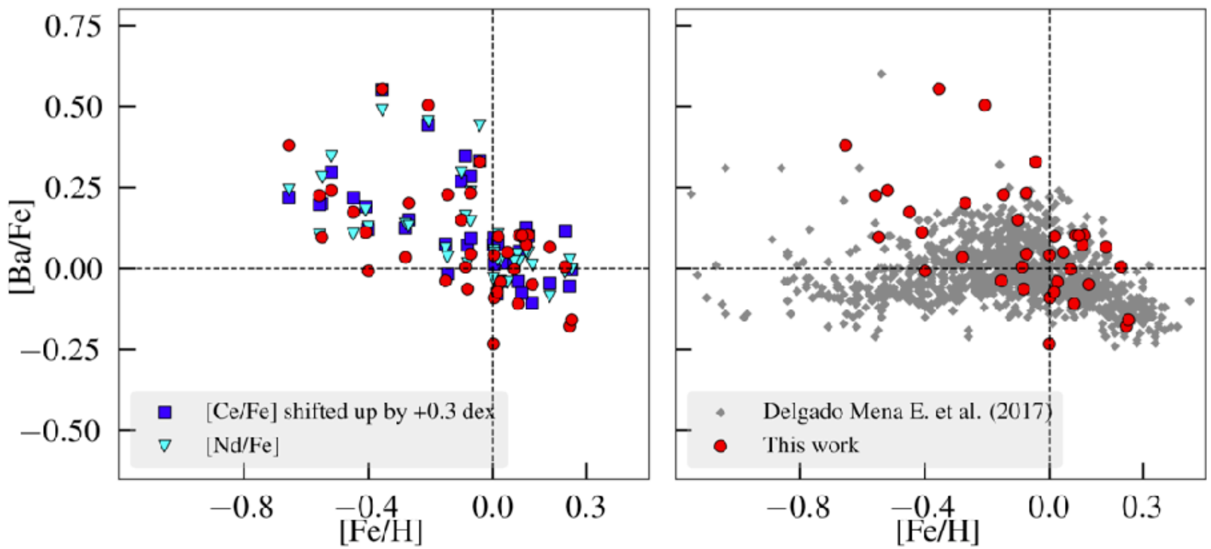

Nandakumar et al., A&A, 2024

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