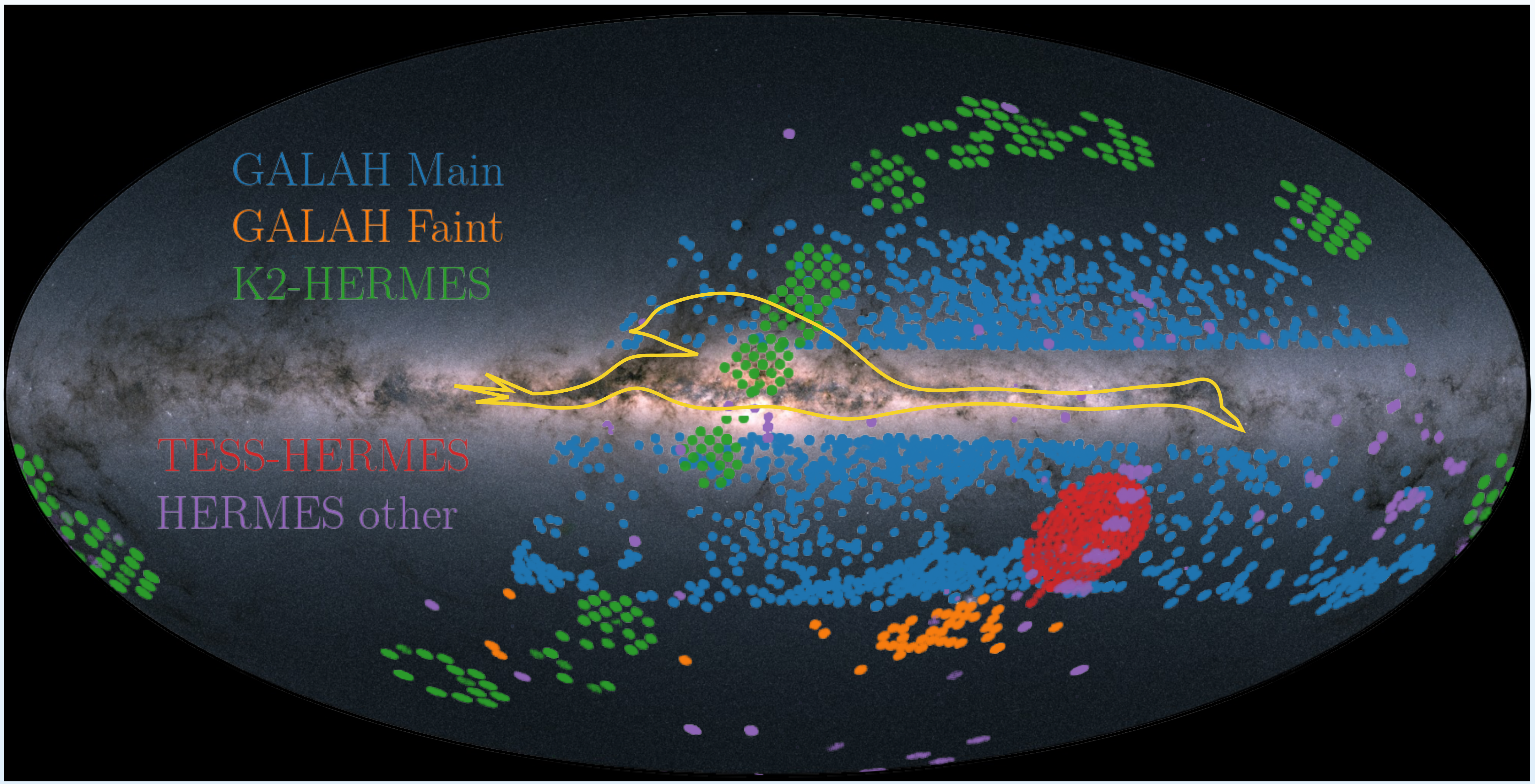
Galactic Archaeology with HERMES

What we have learned from GALAH DR3

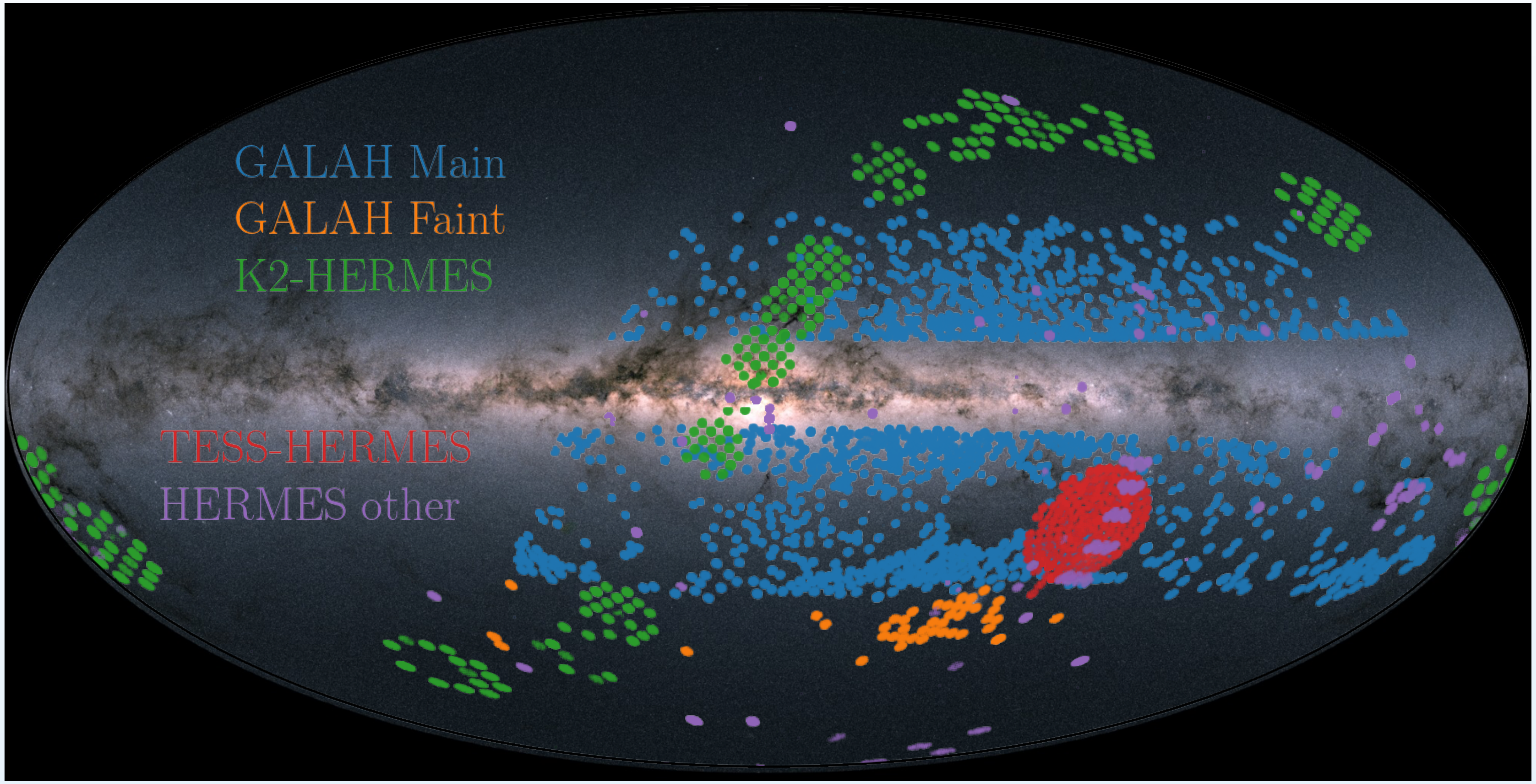
Sven Buder (ANU, @astro_sven)

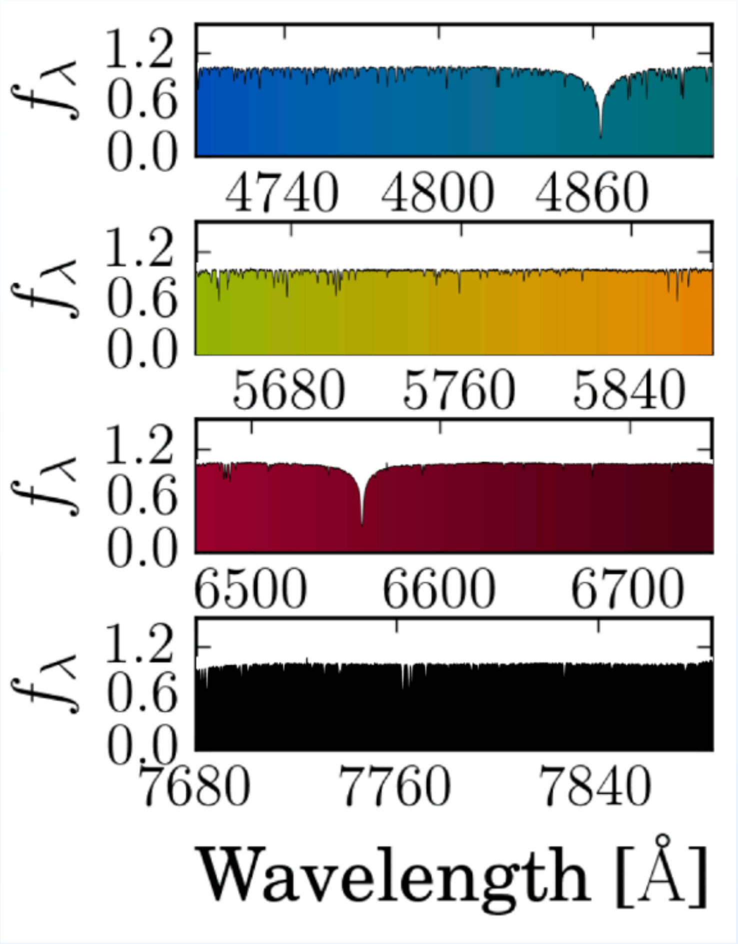


GALAH+ DR3 (Buder et al., 2021, arXiv:2011.02505): ~ 600 000 stars

Galactic Archaeology with HERMES

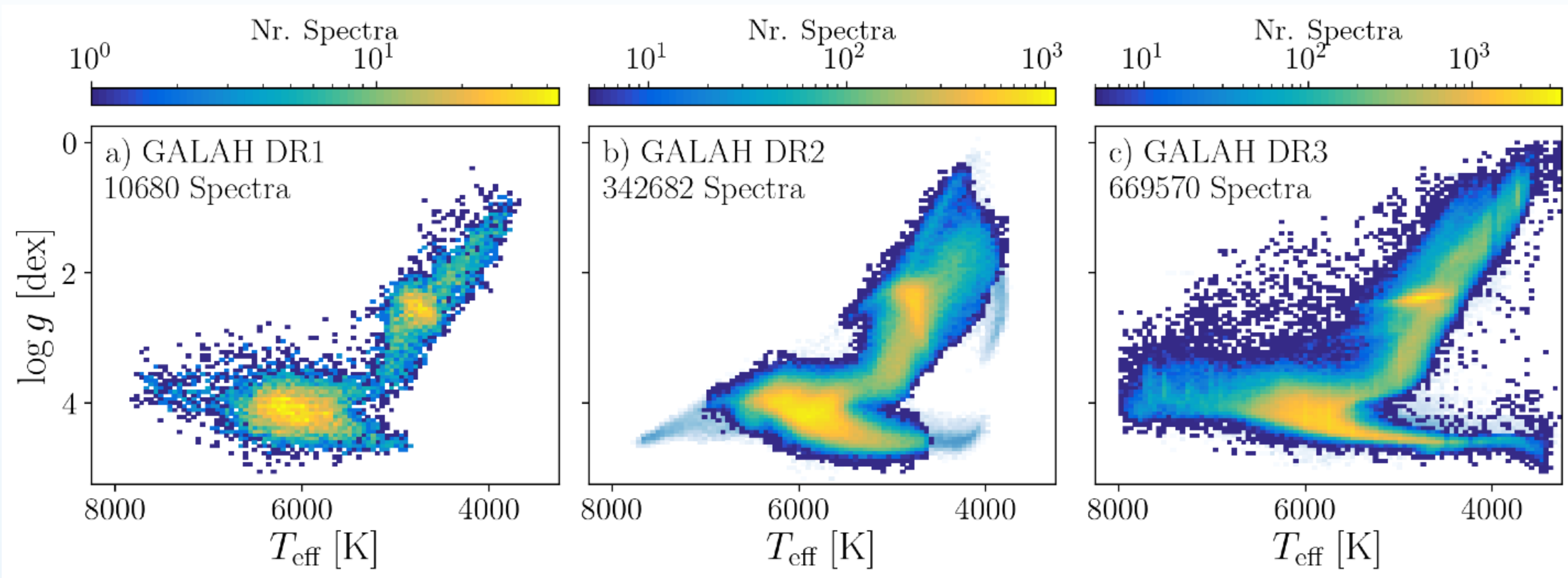
Overview of the survey and its motivation: De Silva et al. (2015)





Coverage:	spatially (81% < 2 kpc) + λ (30 [X/Fe]!),
Quality vs. Quantity:	Nr. = 0.6-1.0 Mio, S/N = 50, R = 28,000,
Complementarity:	100% Gaia (1.5% ϖ unc.)! + TESS + K2

Lessons from GALAH DR3



GALAH DR4

?

Science

Chemistry +
Dynamics + Ages

GALAH DR4

What can we
do better?

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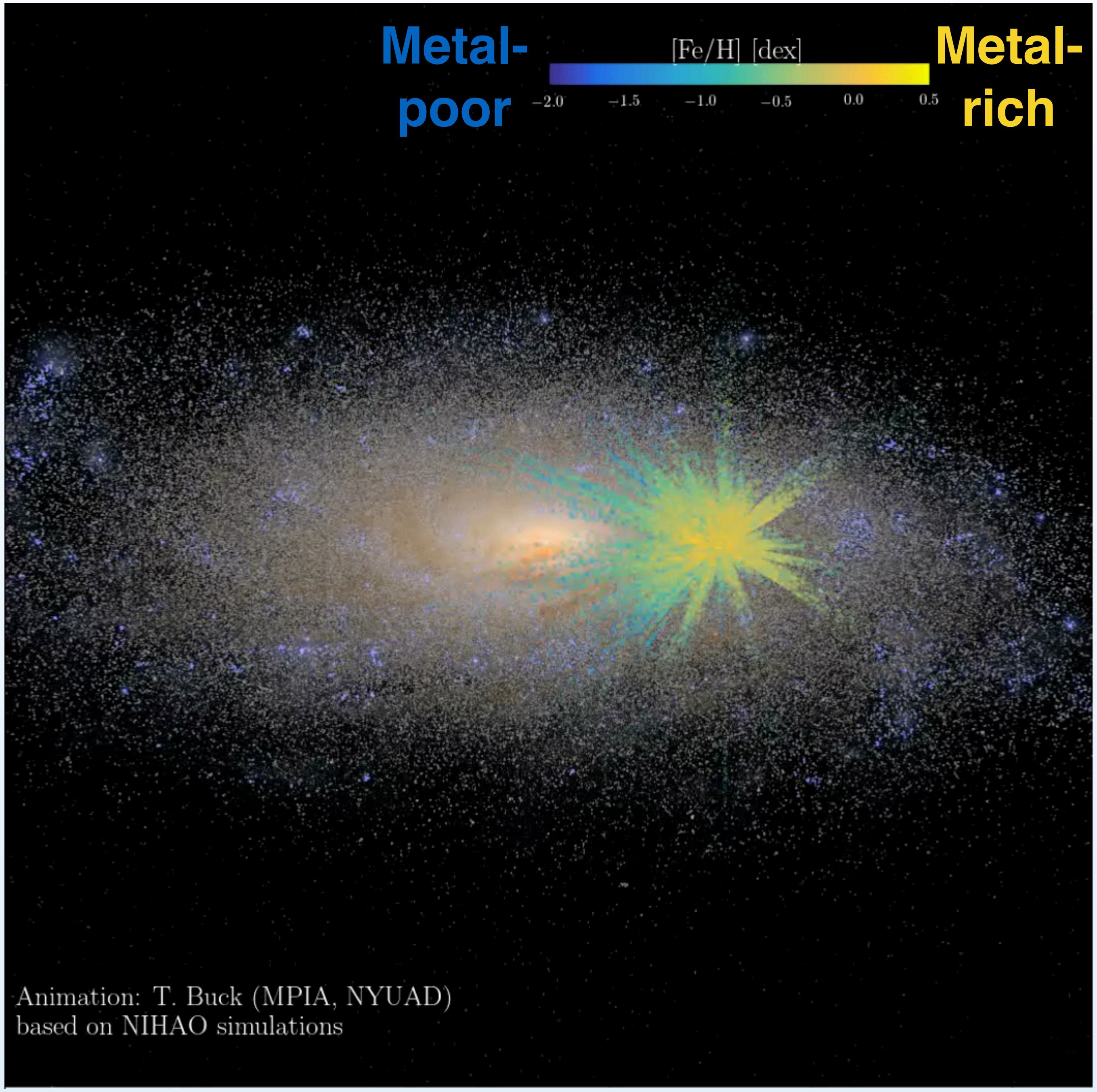
Exploring the Milky Way with GALAH DR3



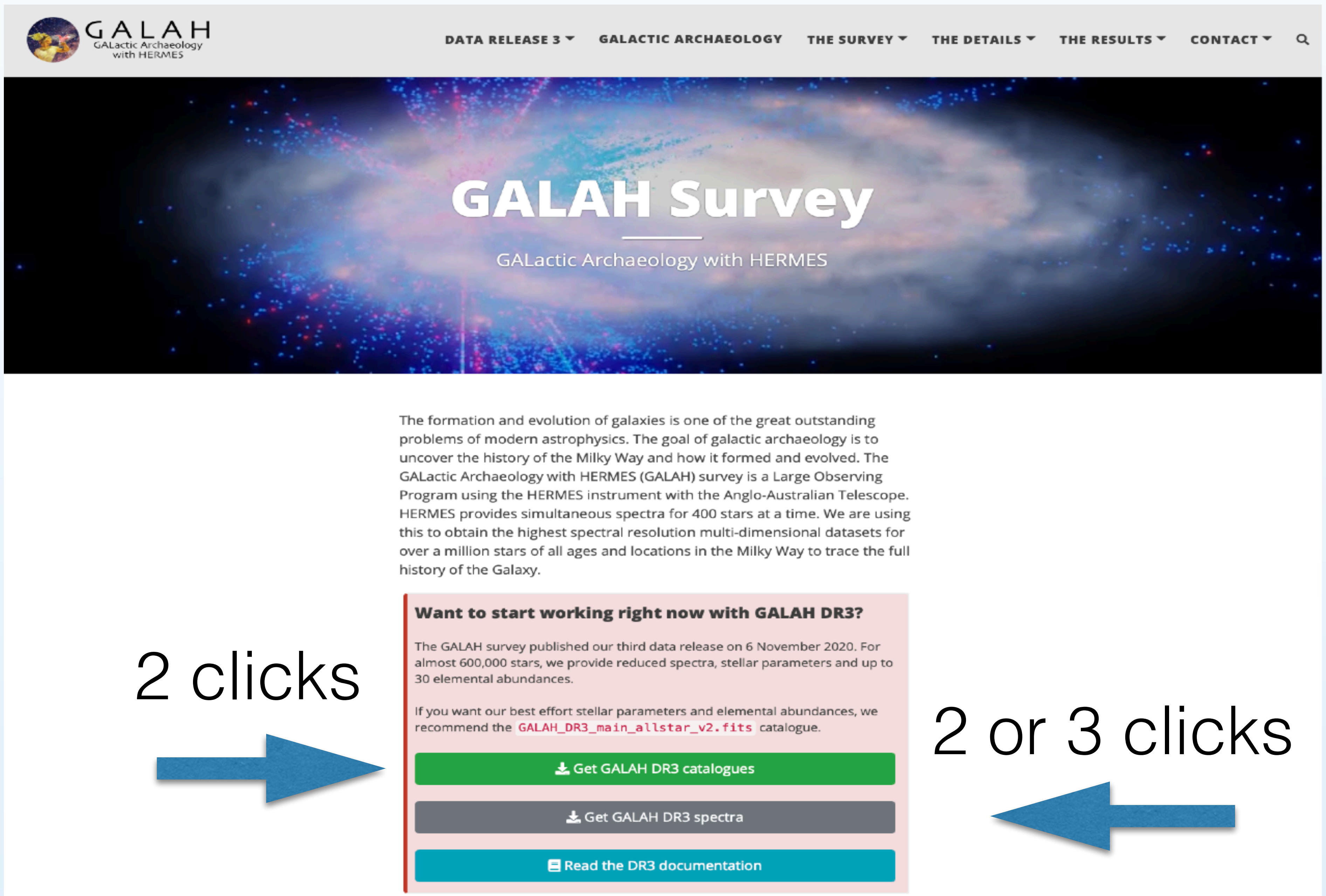
600,000 stars
of the Milky Way

2/3 dwarfs, 1/3 giants

62% young low-α disk
9% young high-α disk
27% old high-α disk
2% with [Fe/H] < -1
4% kinematic halo

GALAH DR3 is easy to access!

www.galah-survey.org



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What have we learned with GALAH DR3 + Gaia?

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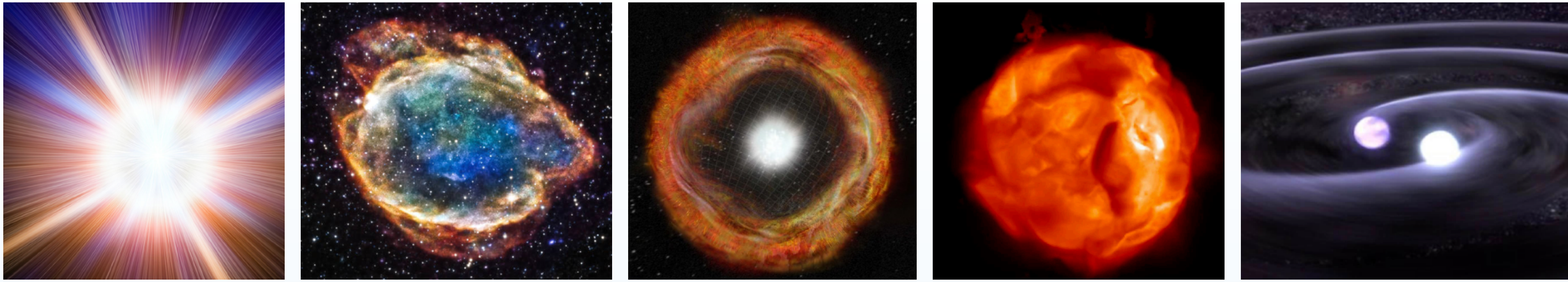
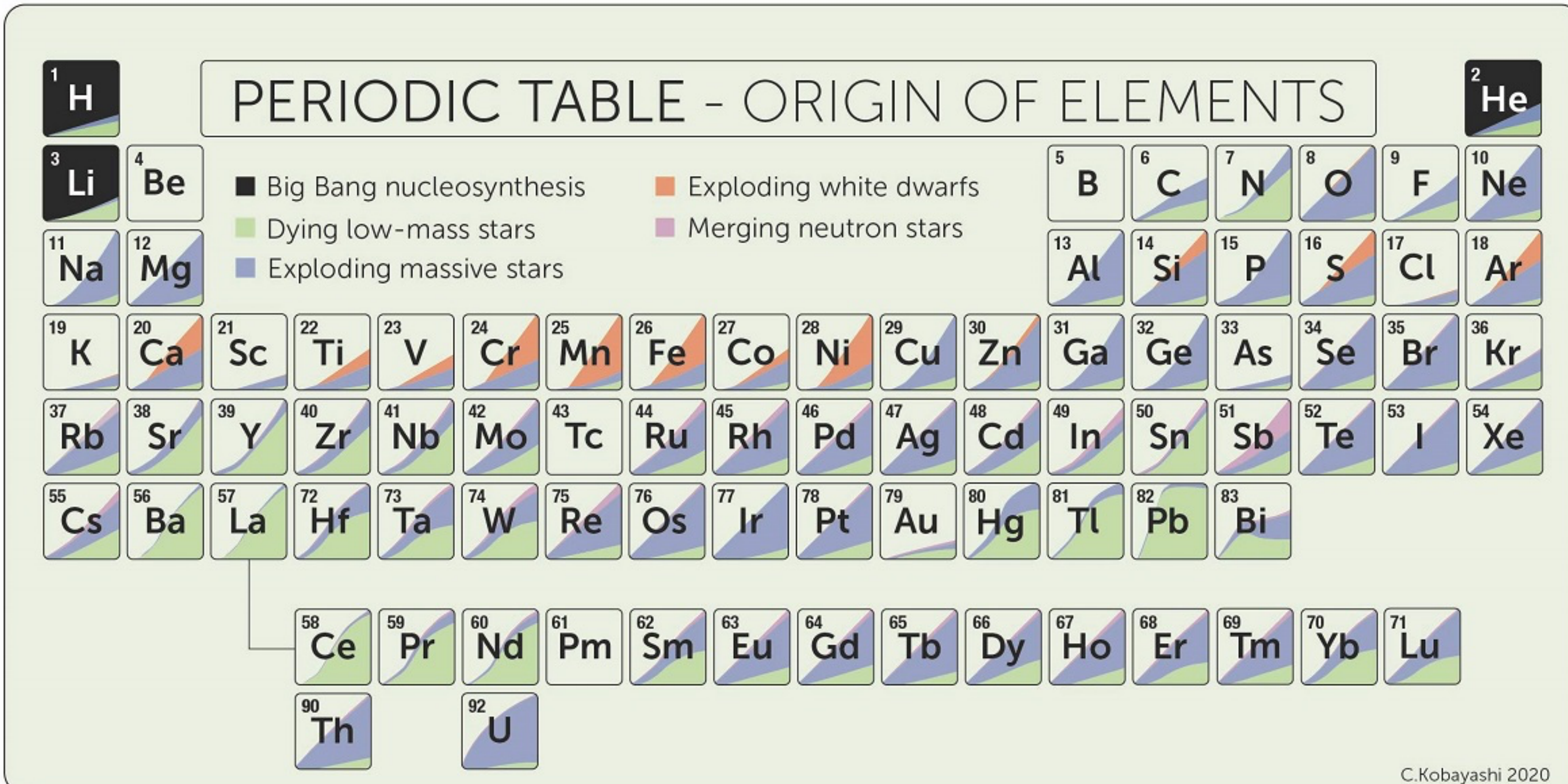
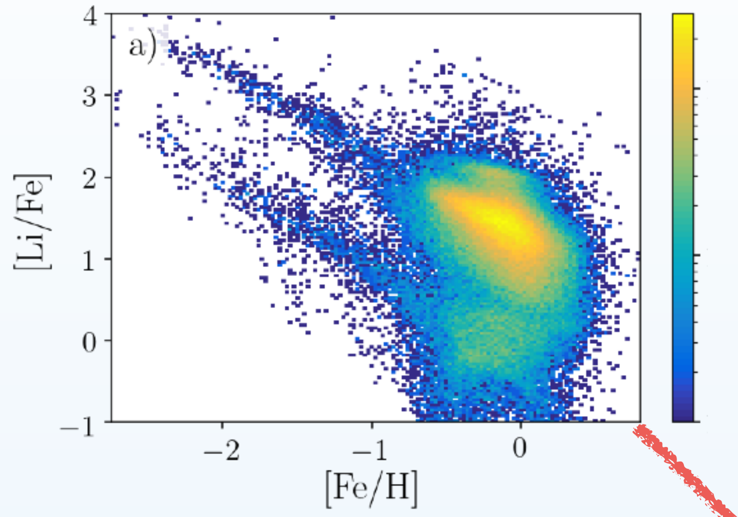
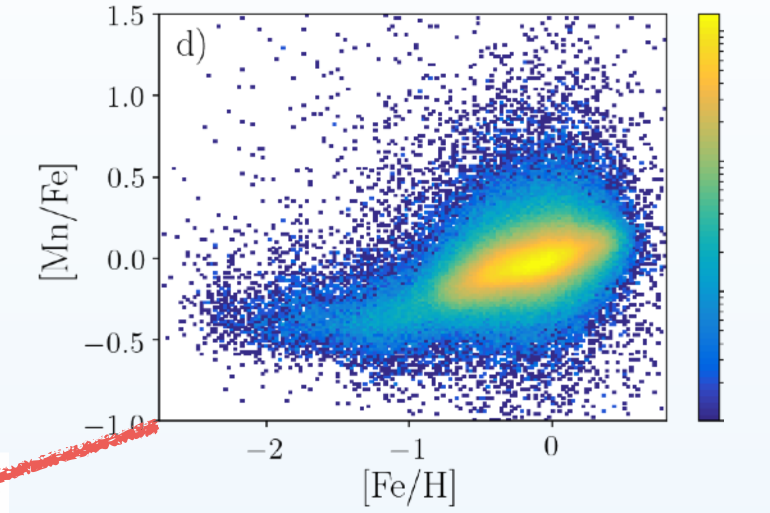


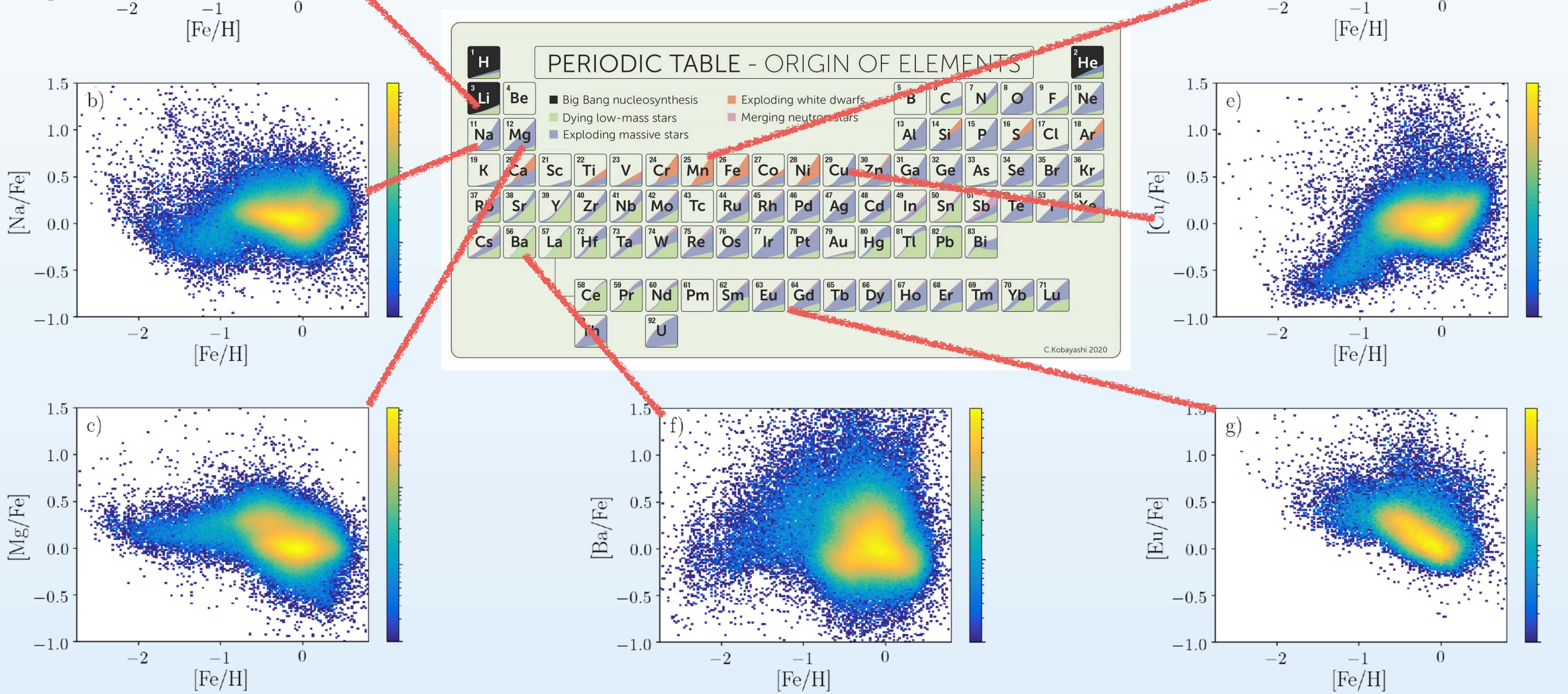

PERIODIC TABLE - ORIGIN OF ELEMENTS
Big Bang nucleosynthesis
Dying low-mass stars
Exploding massive stars
Exploding white dwarfs
Merging neutron stars
1 H 2 He
3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba 57 La 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi
58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb 71 Lu
90 Th 92 U
C.Kobayashi 2020

Element abundances in the Milky Way



Enrichment/depletion imprints different patterns onto different elements





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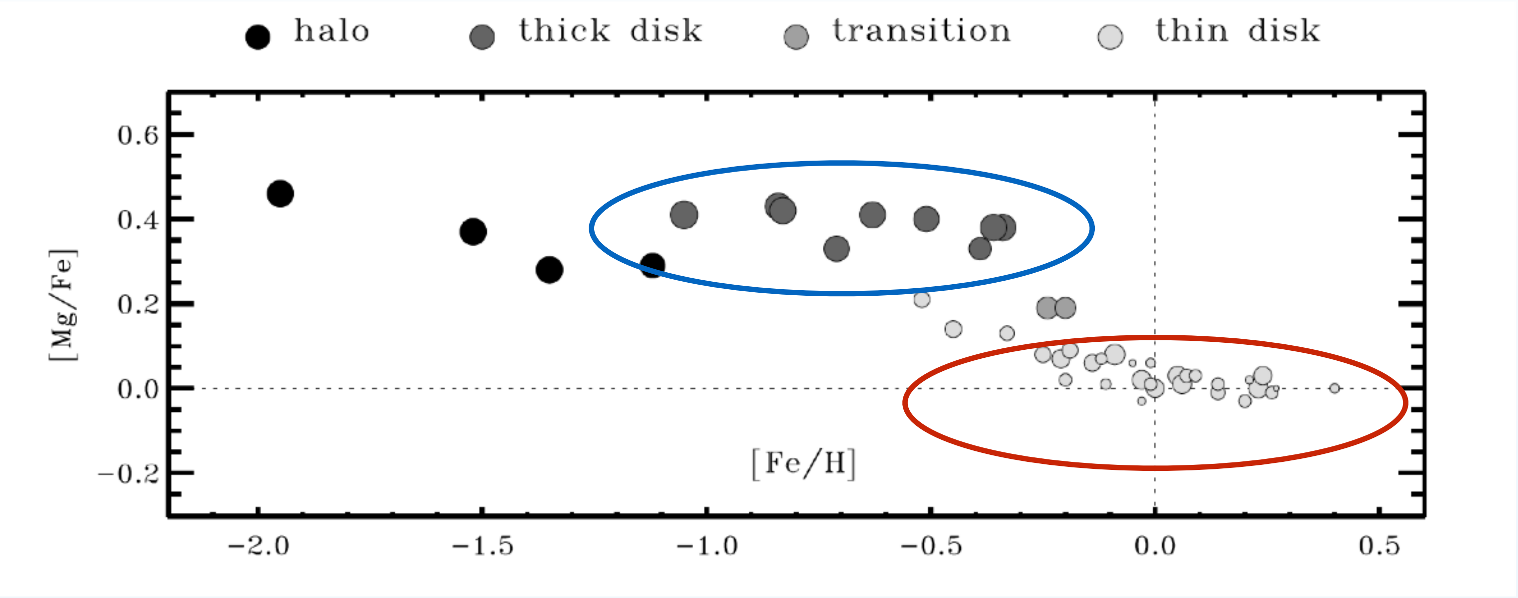
THROUGH THICK AND THIN DISK



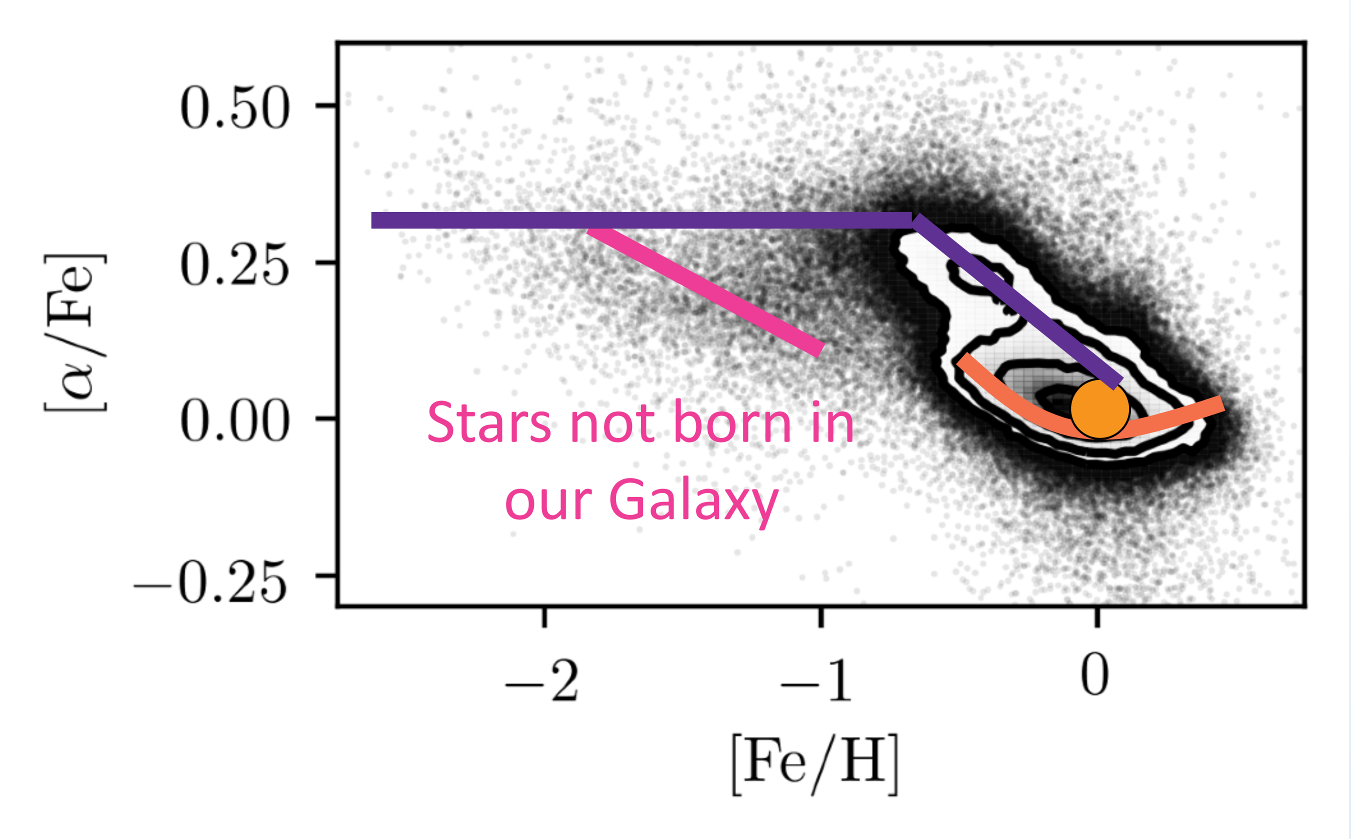
Fuhrmann 1998 (~50 stars)

Top-heavy IMF
SFR burst strength
SNII / SNIa

Galactic trends? Halo / Disk / Bulge and their transition?

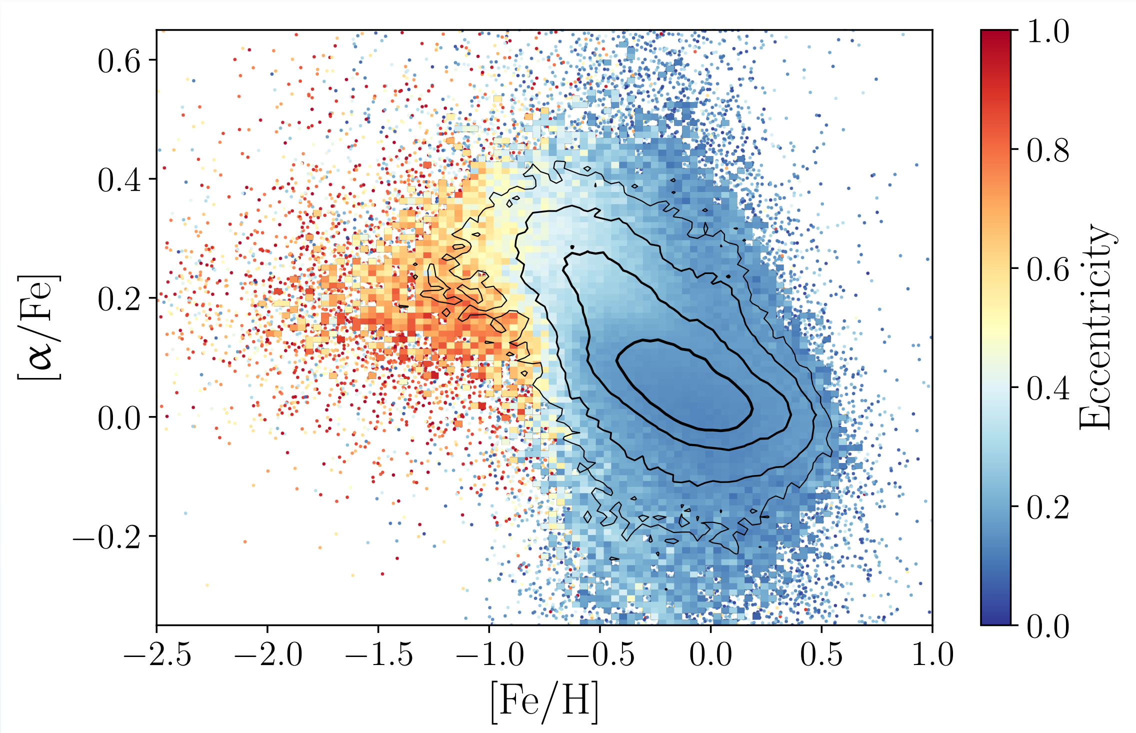
Trends beyond [Mg/Fe] and [Fe/H]?

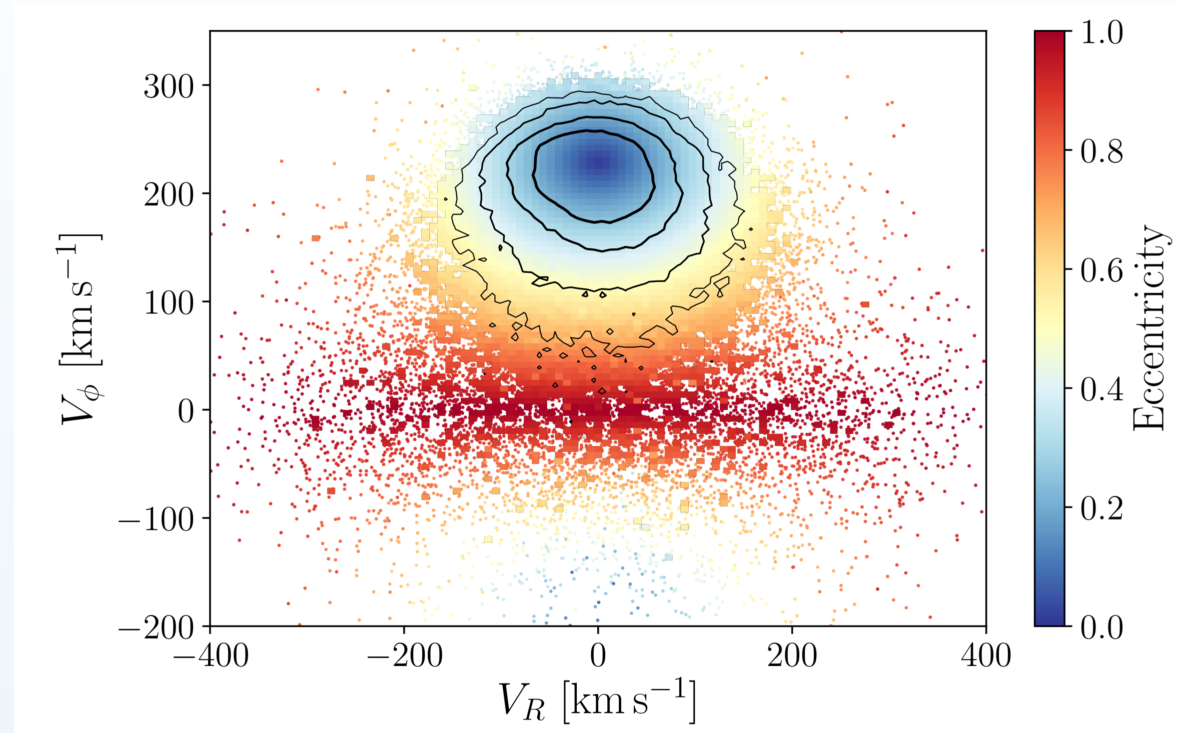
…?

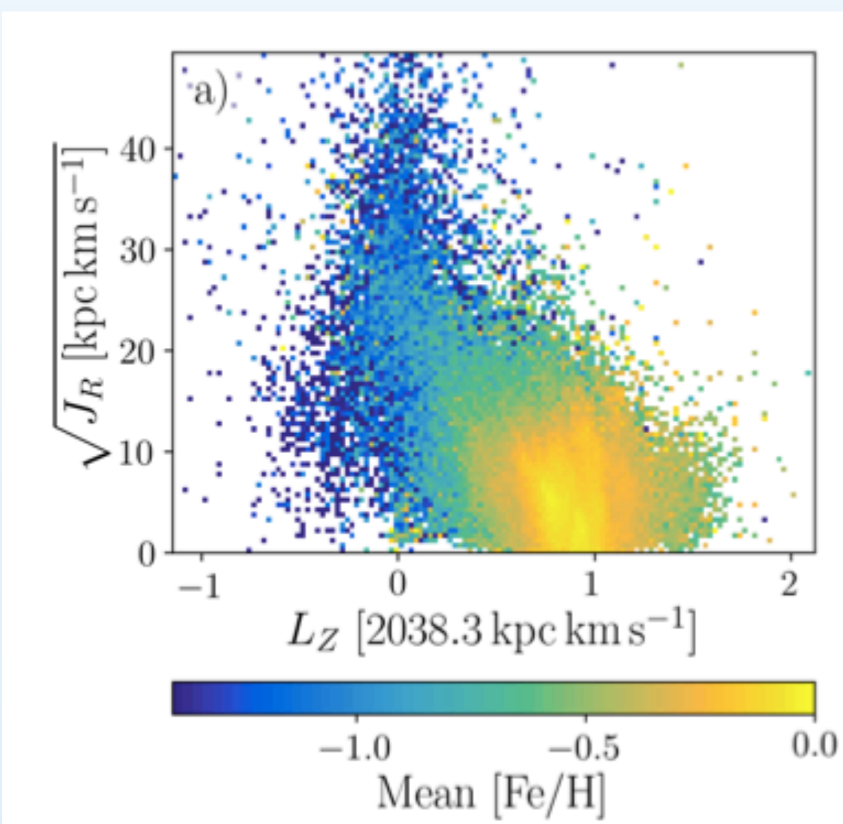


Buder et al. 2021 (~600,000 stars)

Adding dynamics: Chemodynamics

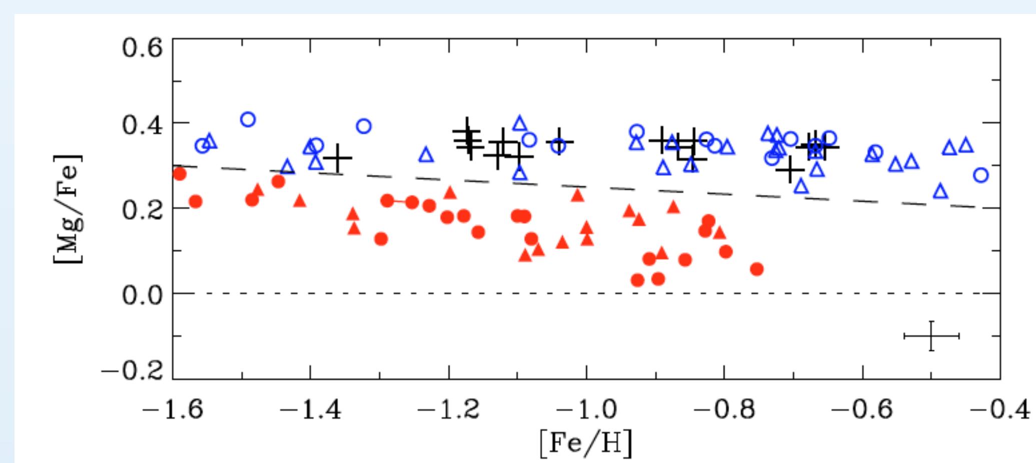






high-α kinematic halo

low-α kinematic halo



Nissen & Schuster (2010-2014)

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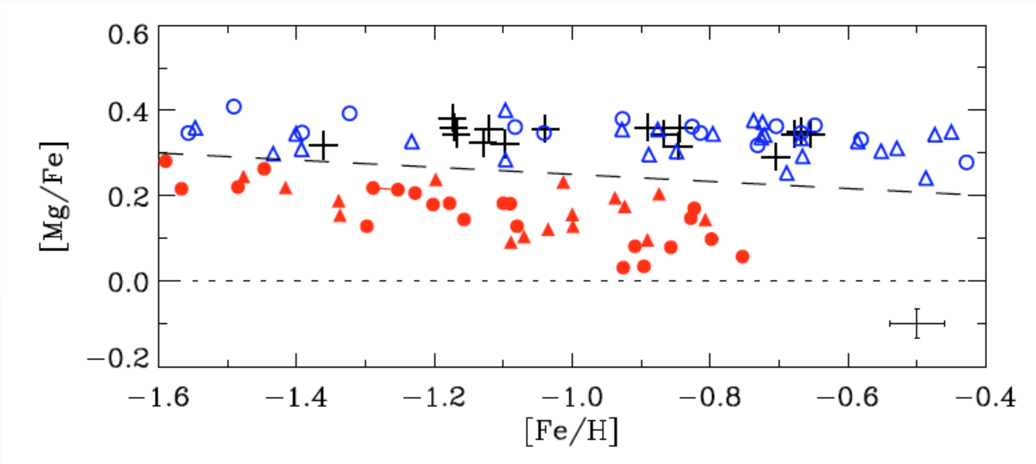
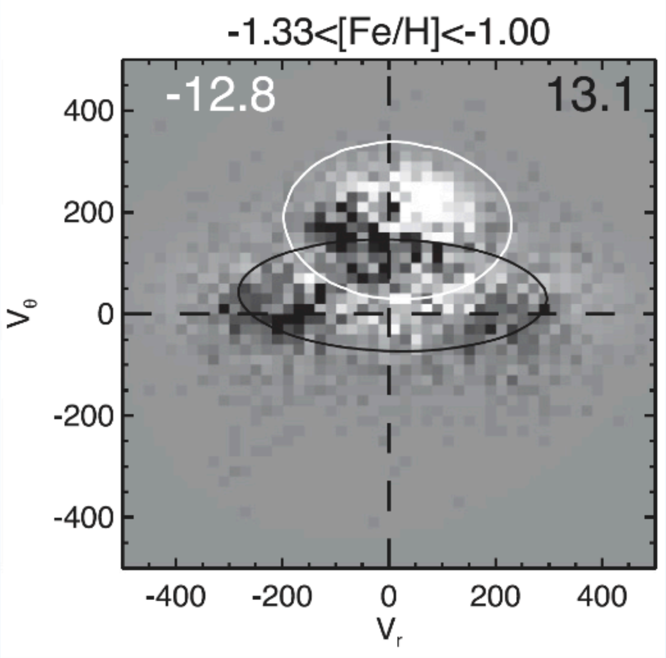
Accreted stars: Gaia-Sausage-Enceladus

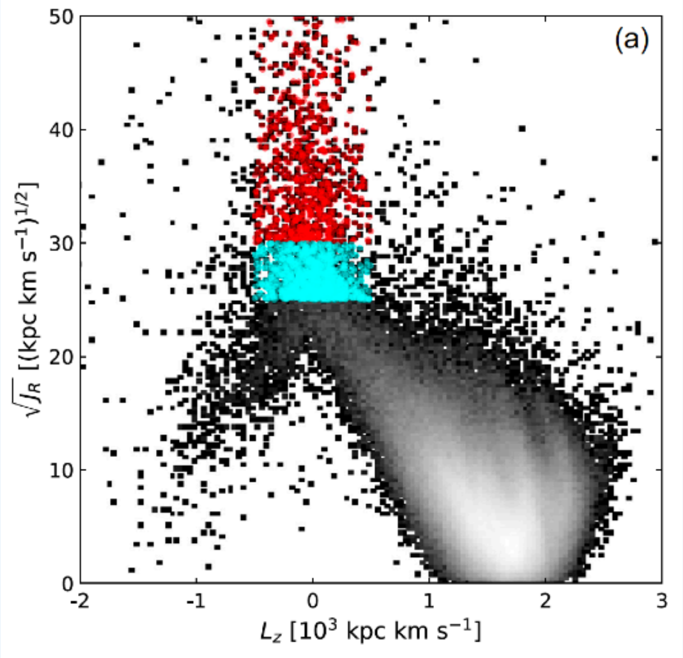
high-α kinematic halo
low-α kinematic halo



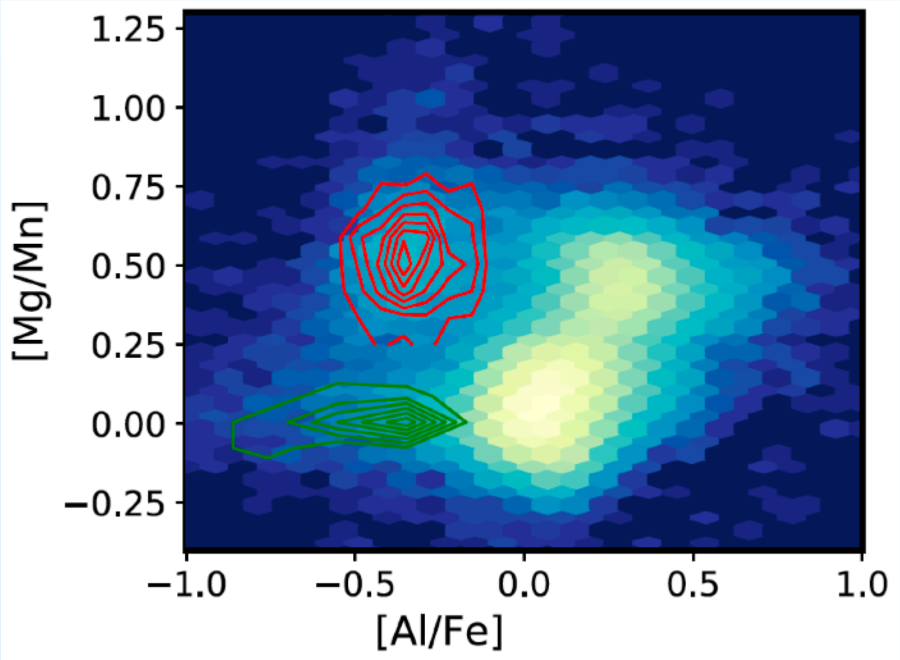
Nissen & Schuster (2010-2014)



Belokurov et al. (2018)



Helmi et al. (2018), Feuillet et al. (2020)



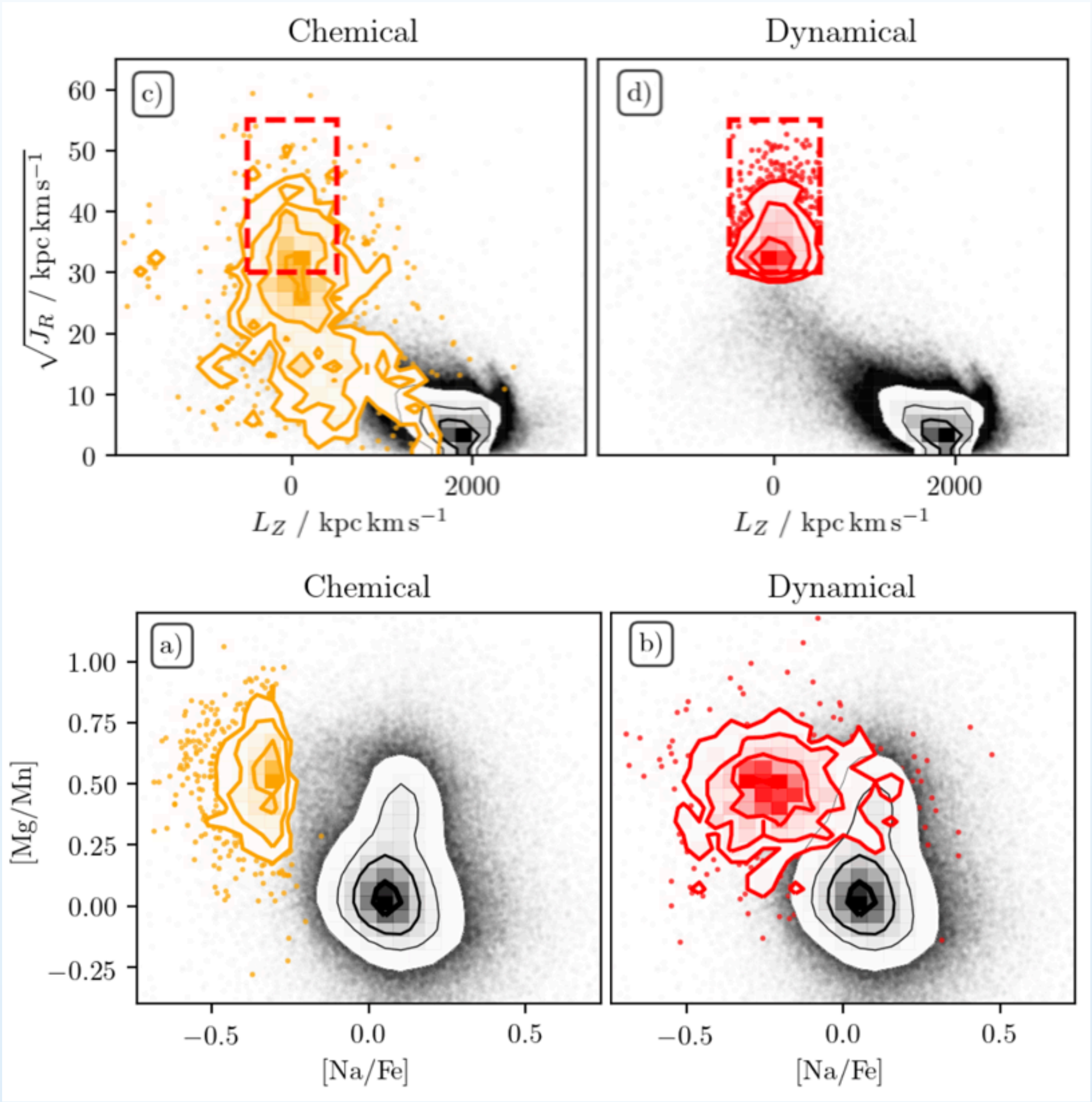
Das, Hawkins, Jofré (2020)

SUBSTRUCTURE IN THE GALACTIC HALO

How large is the overlap of the dynamically
and chemically identified substructures actually?

Study dynamical extend via **chemical** selection

GSE is **chemically** different from **disk**



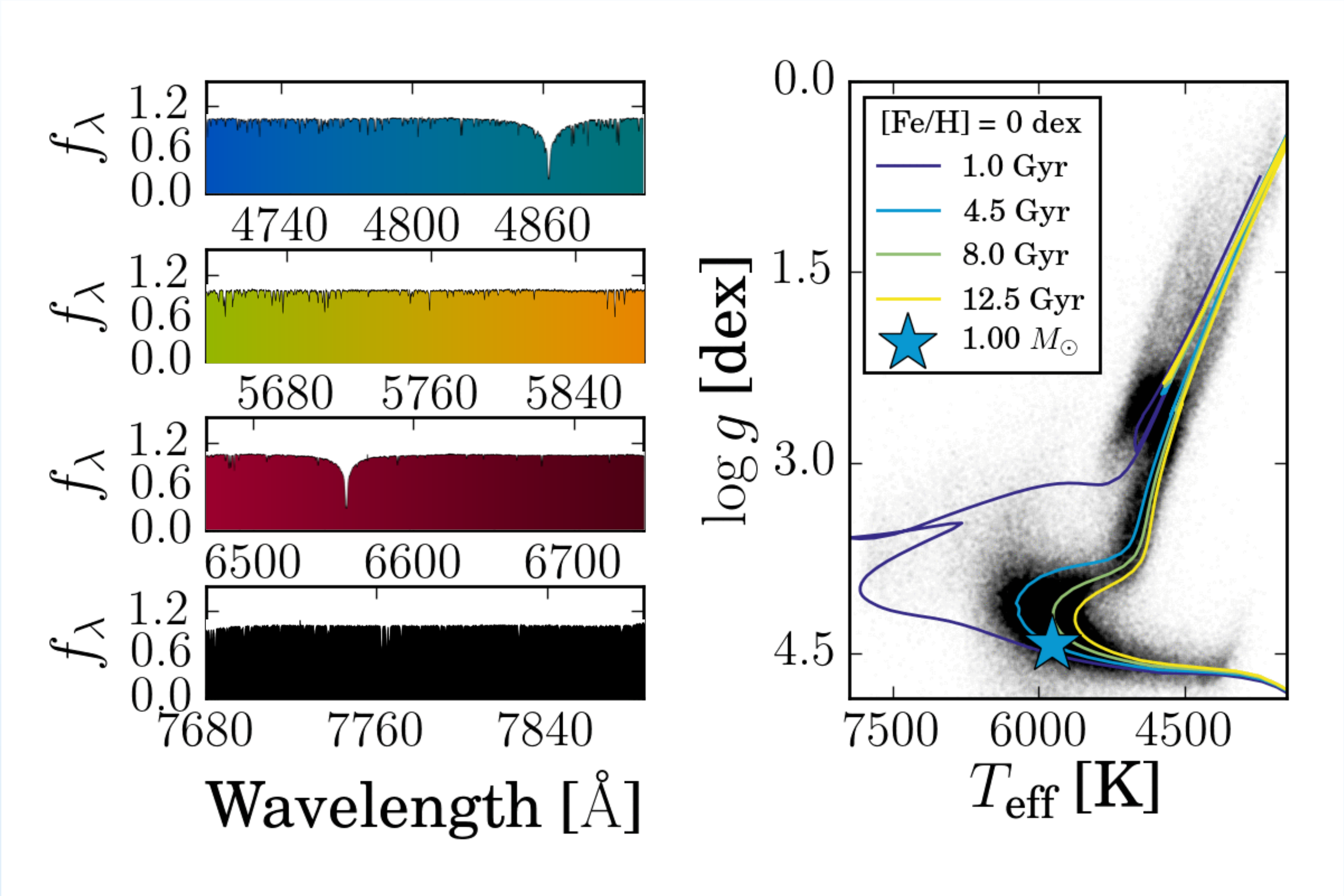
GSE is **dynamically** different from **disk**

Study chemical extend via **dynamical** selection

Buder et al. (2021b)

What have we learned for GALAH DR4?

How GALAHs see the stars



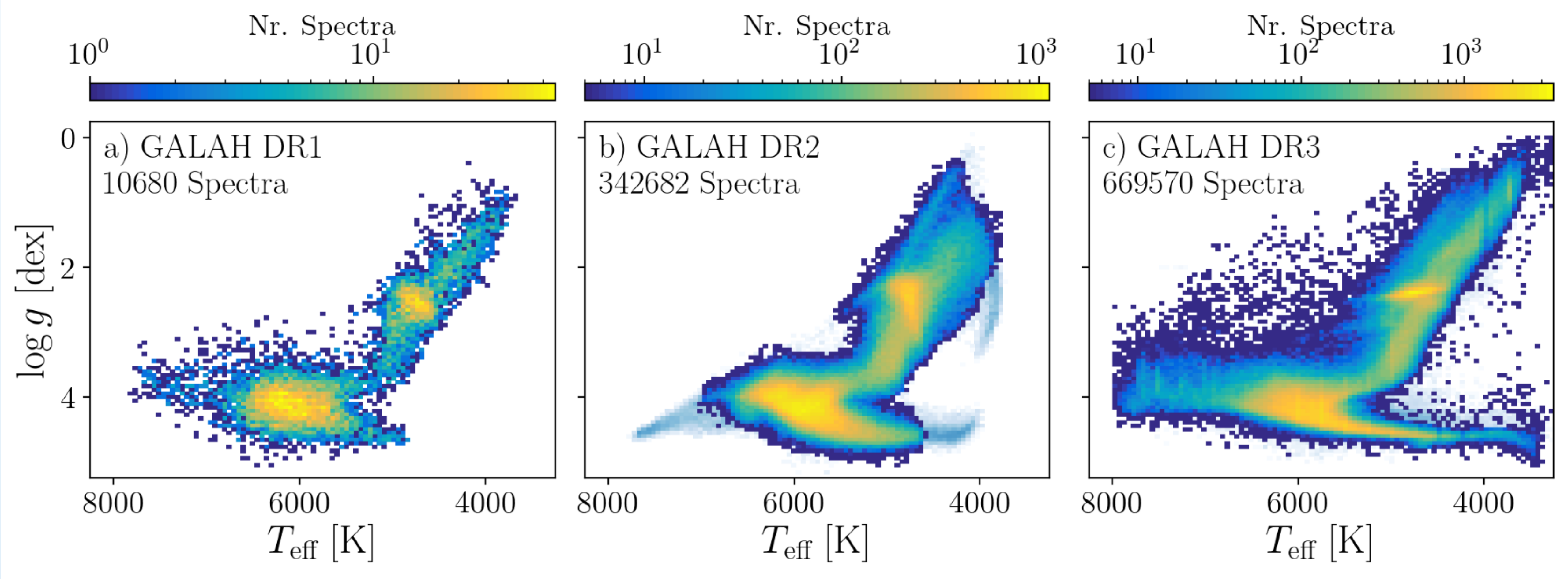
GALAH Spectrum Analysis

A hybrid of Spectroscopy Made Easy and interpolation methods:

DR1+2: SME + The Cannon

DR3: SME + *Gaia* DR2

DR4: SME + neural networks + *Gaia* (e)DR3



Martell et al. (2017) Buder et al. (2018) Buder et al. (2021)

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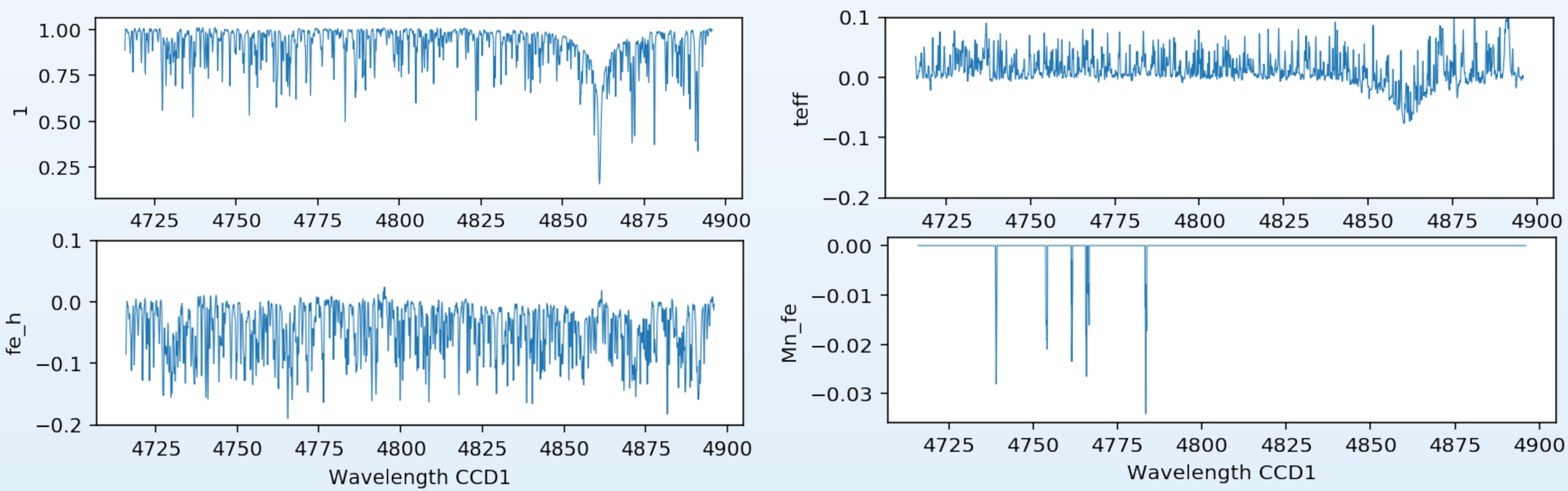
Challenges GALAH has overcome

- **Spectrum analysis of up to 1 million optical spectra?!**
  -> Developed new pipeline to analyse spectra (Buder et al. 2018):
  combine classic spectrum synthesis + new data-driven method

$$f_{n,\lambda} = f(\Theta|l)_n = \Theta_\lambda^T \cdot l_n + \text{noise} + \text{scatter}$$

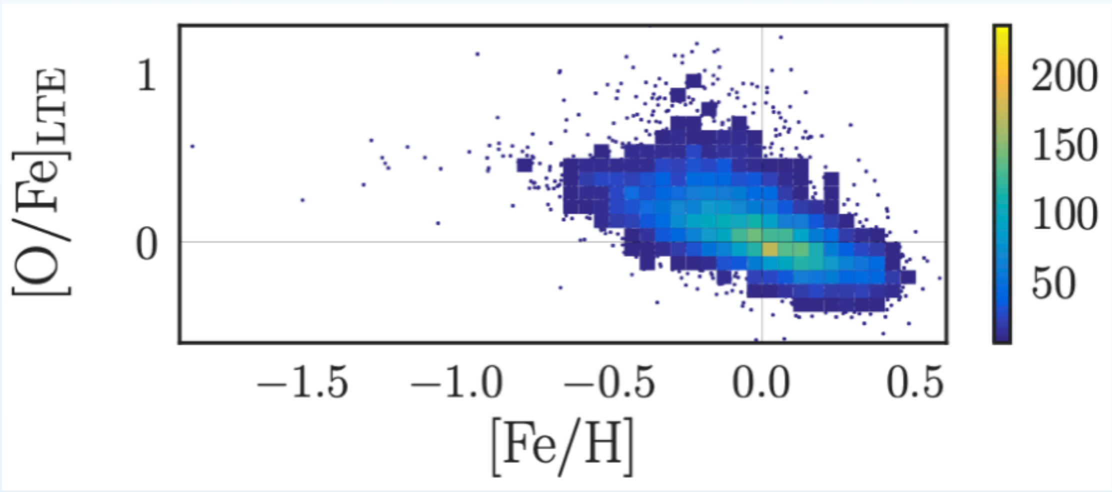
$$f_{n,\lambda} = 1 + c_{l1} \cdot T_\text{eff} + c_{l2} \cdot [\text{Fe/H}] + \ldots c_{l12} \cdot T_\text{eff} \cdot [\text{Fe/H}] \ldots \ldots c_{s11} \cdot T_\text{eff}^2 \ldots$$

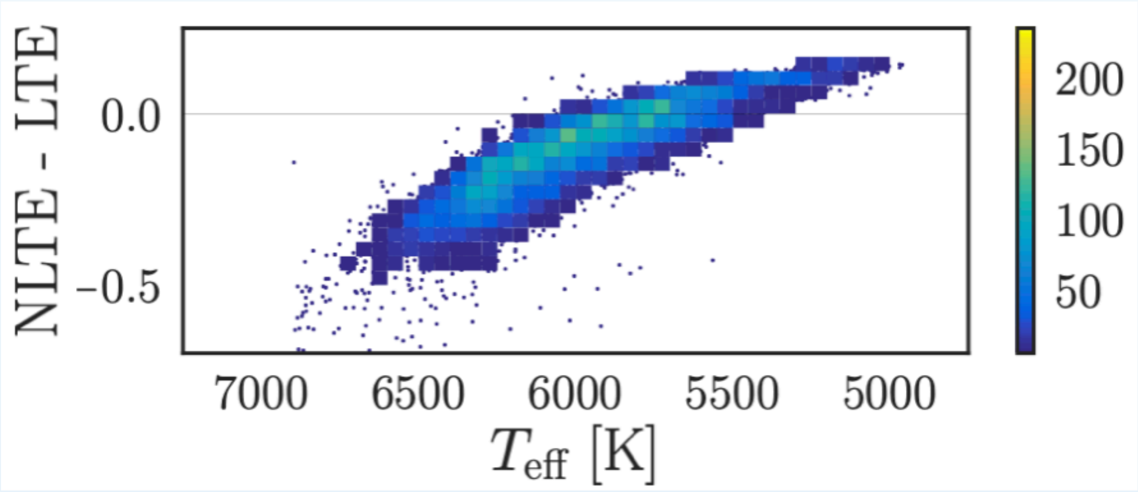


The Cannon (Ness et al. 2015), The Payne (Ting et al. 2019)

Challenges GALAH has overcome

- **Spectrum analysis of up to 1 million optical spectra?!**
  -> state-of-the-art stellar physics (1D NLTE, Amarsi et al. 2021)





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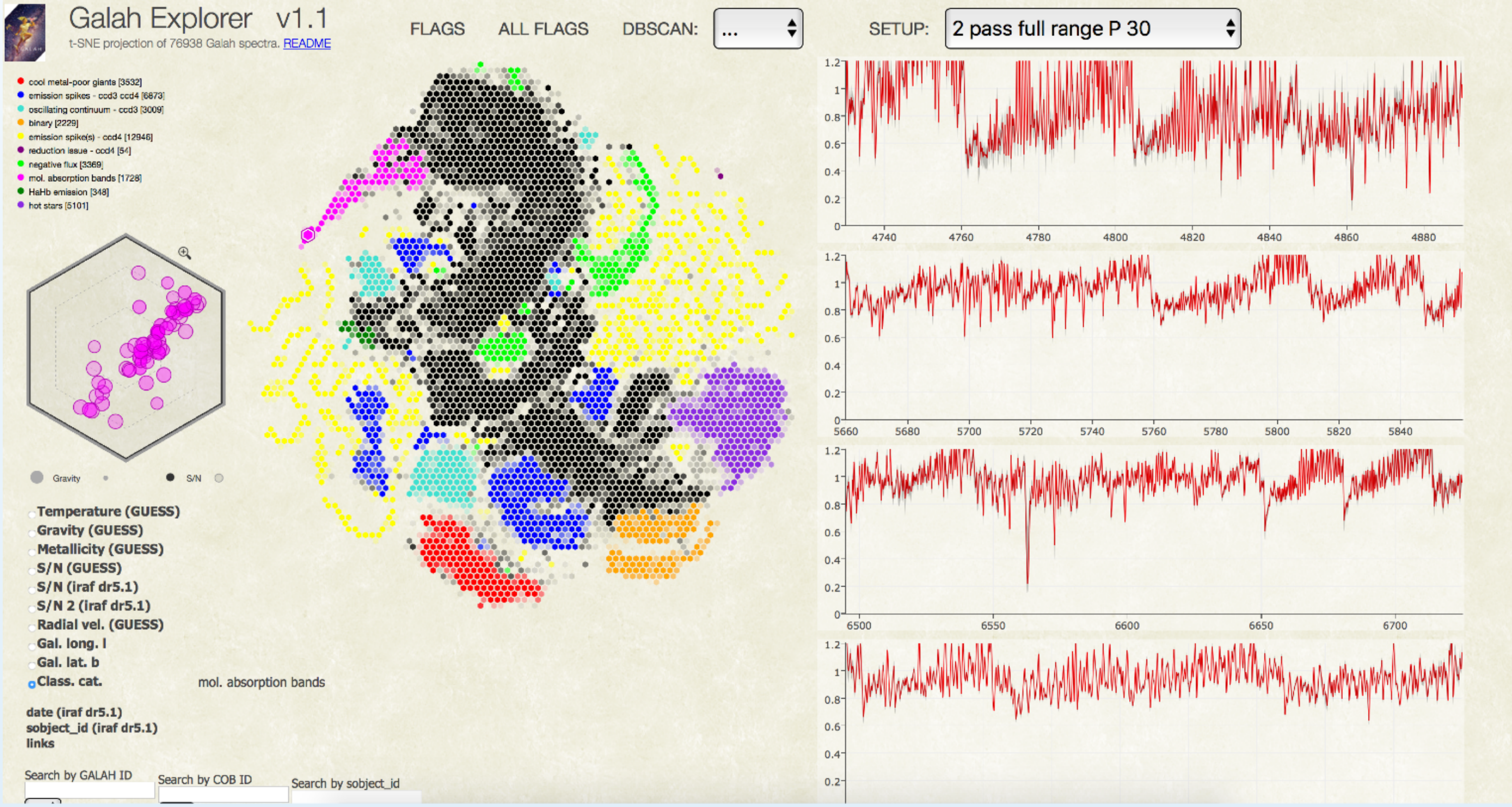
Challenges GALAH has overcome

- **Spectrum analysis of up to 1 million optical spectra?!**
  -> Classification of spectra by how similar they are:
  binary stars, stars with emission, bad spectra, etc.



tSNE (Traven et al. 2017)

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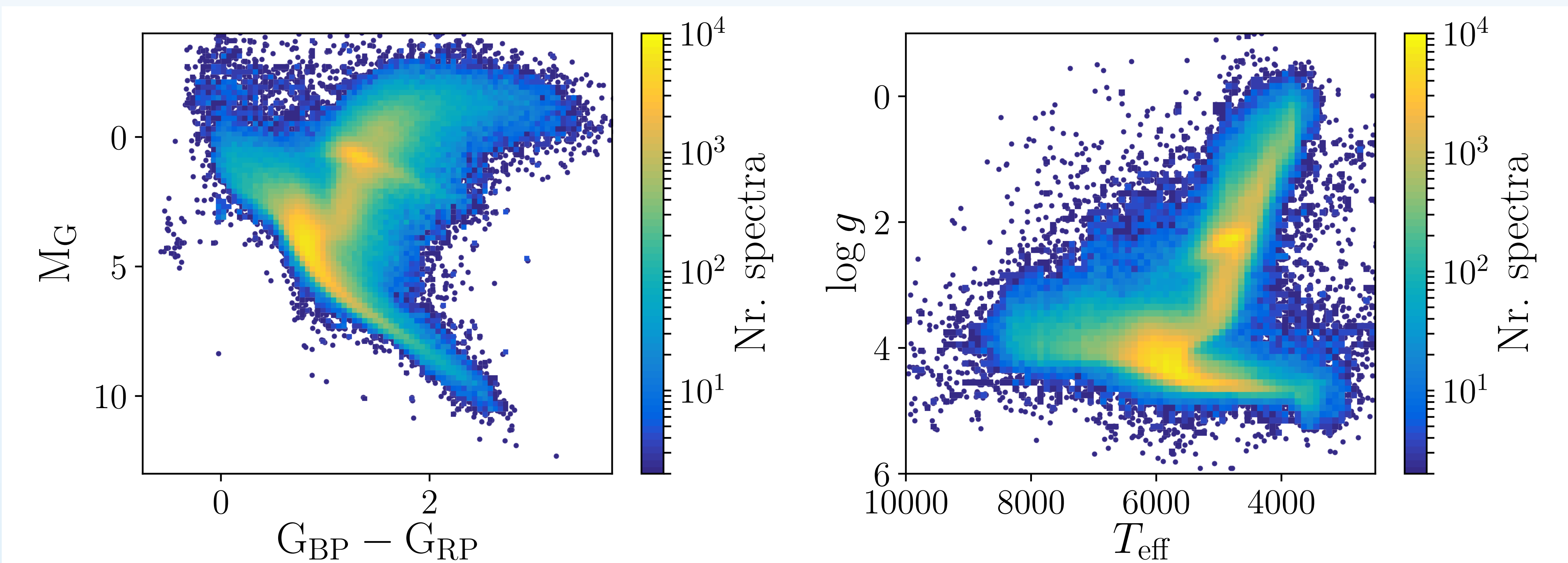
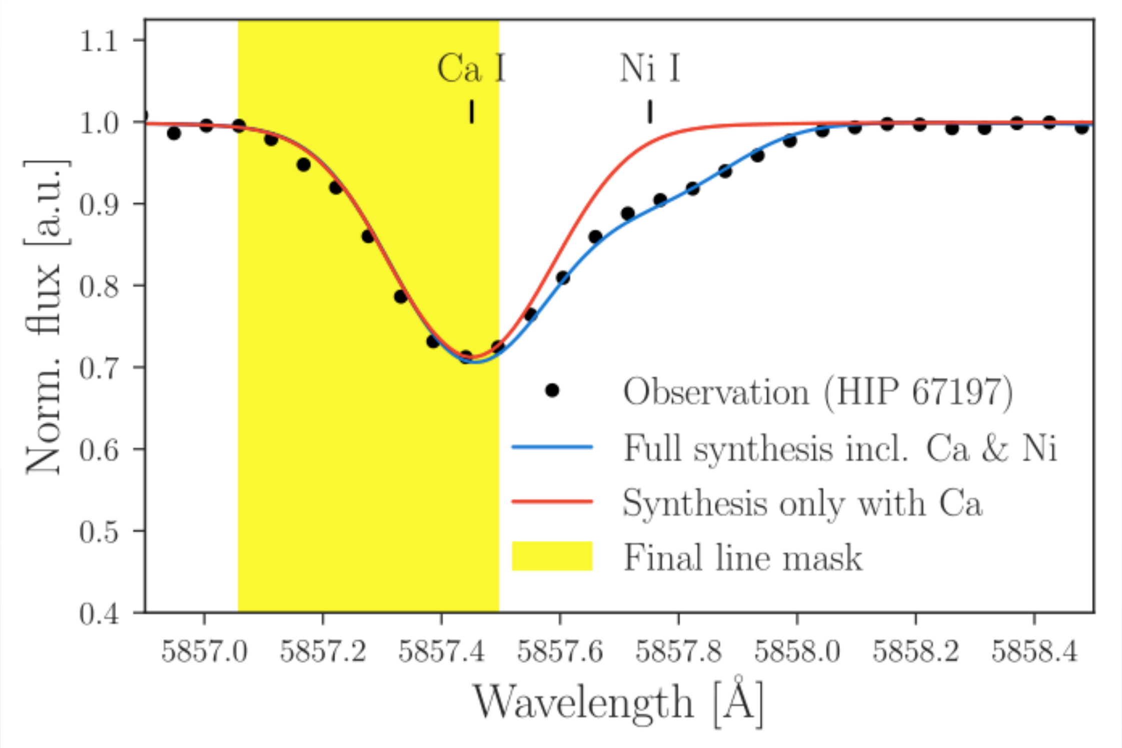
Challenges GALAH has overcome

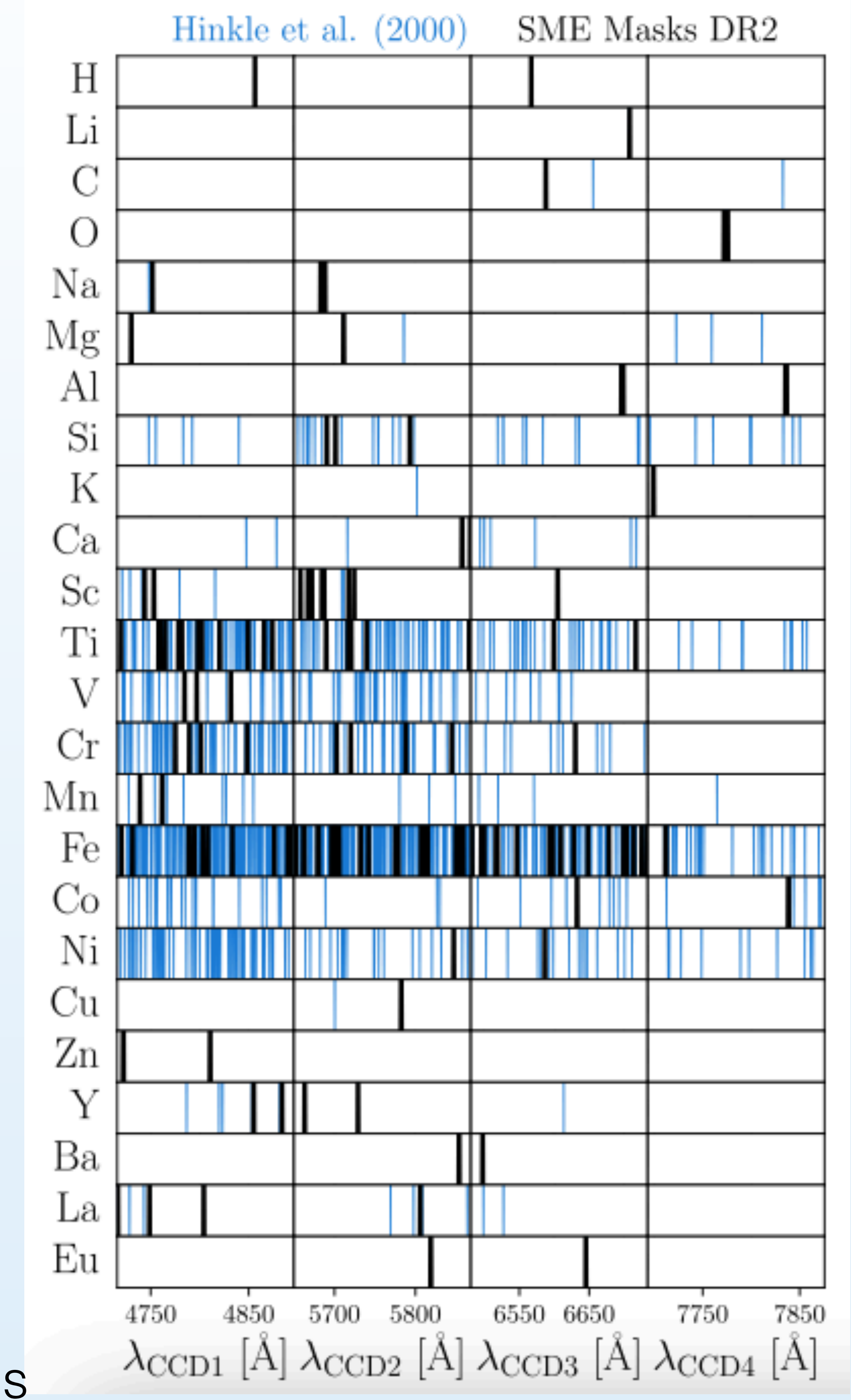
- **Many elements, but not enough information on atmospheric parameters:**
  -> external info from Gaia + photometry (Buder et al. 2021)
  -> external info from asteroseismology (Sharma et al. 2018, 2019)



$$\log g = \log g_\odot + \log \frac{\mathcal{M}}{\mathcal{M}_\odot} + 4 \log \frac{T_{\rm eff}}{T_{\rm eff,\odot}} - \log \frac{L_{\rm bol}}{L_{\rm bol,\odot}}$$

Can we use more lines?





DR1-DR3:

Measure only a few trustworthy* lines
Fit stellar parameters first, then
Measure each element individually

DR4:

Use all reasonable lines and molecules
at once that actually influence the spectra

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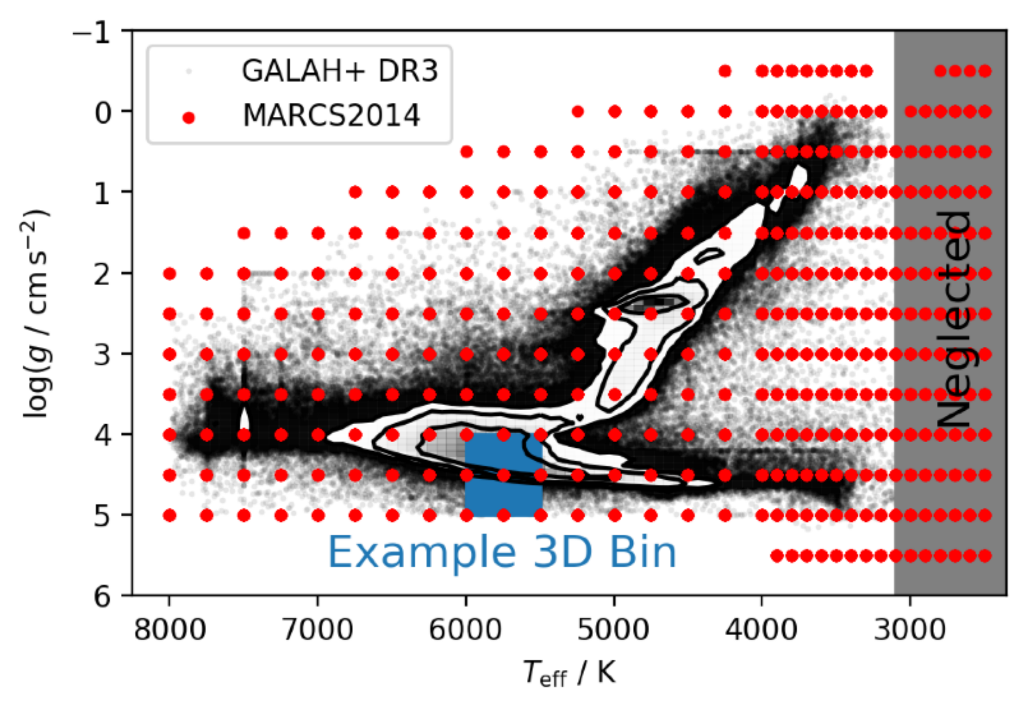
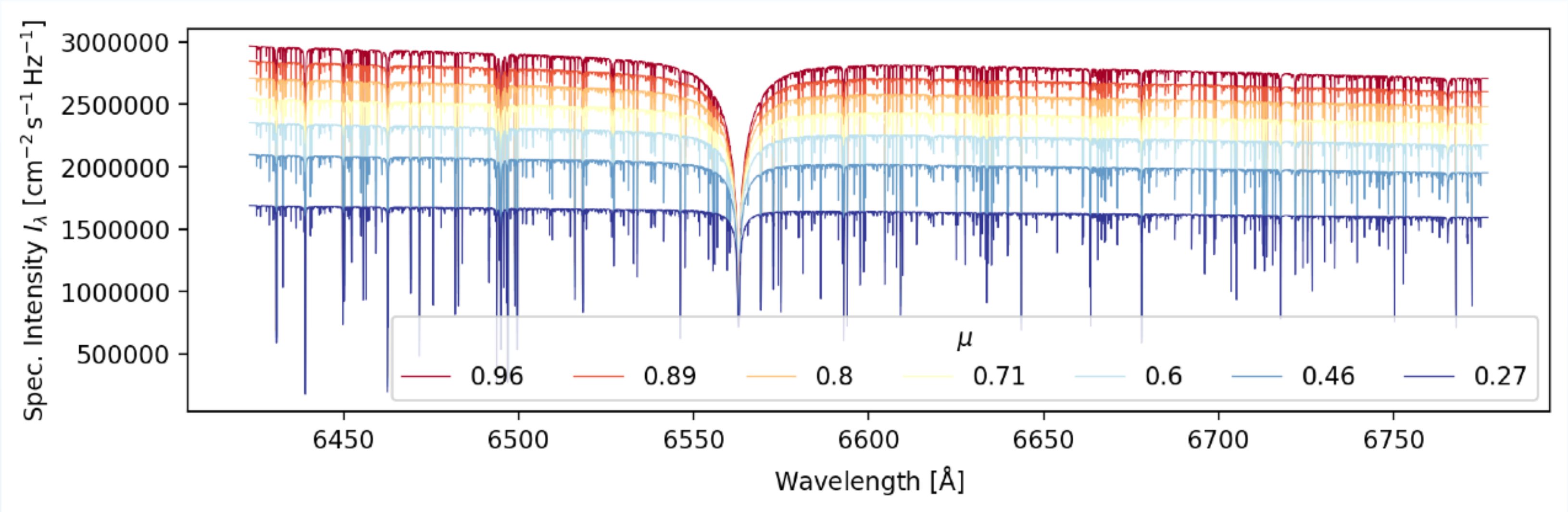
* with exp. log(gf) + no/little blends

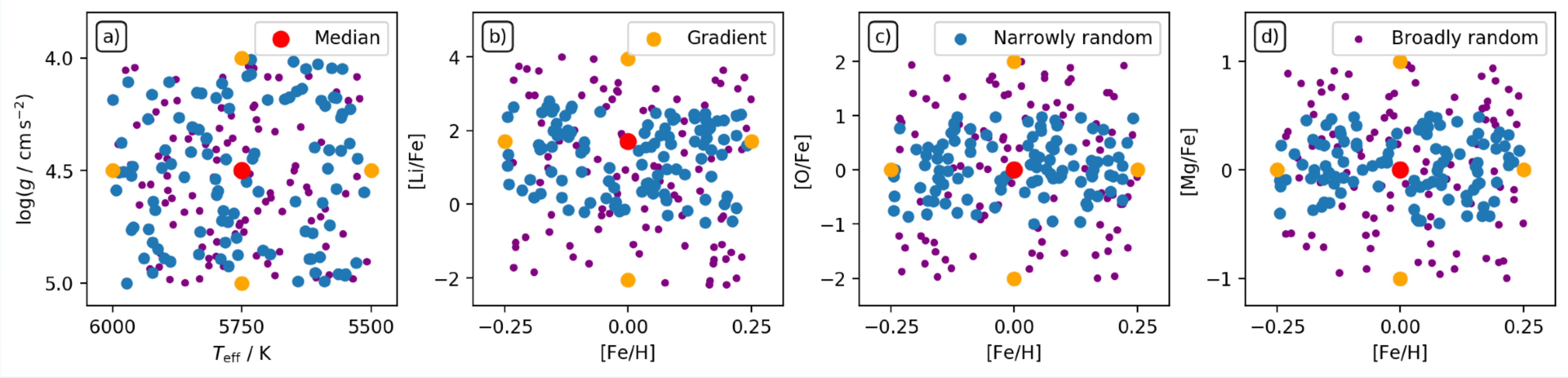
How can we do that best? á la "stellar twins" in 3D bins



Use SME to compute spectra



Sample stellar parameters + abundances in small bins of Teff/logg/[Fe/H]



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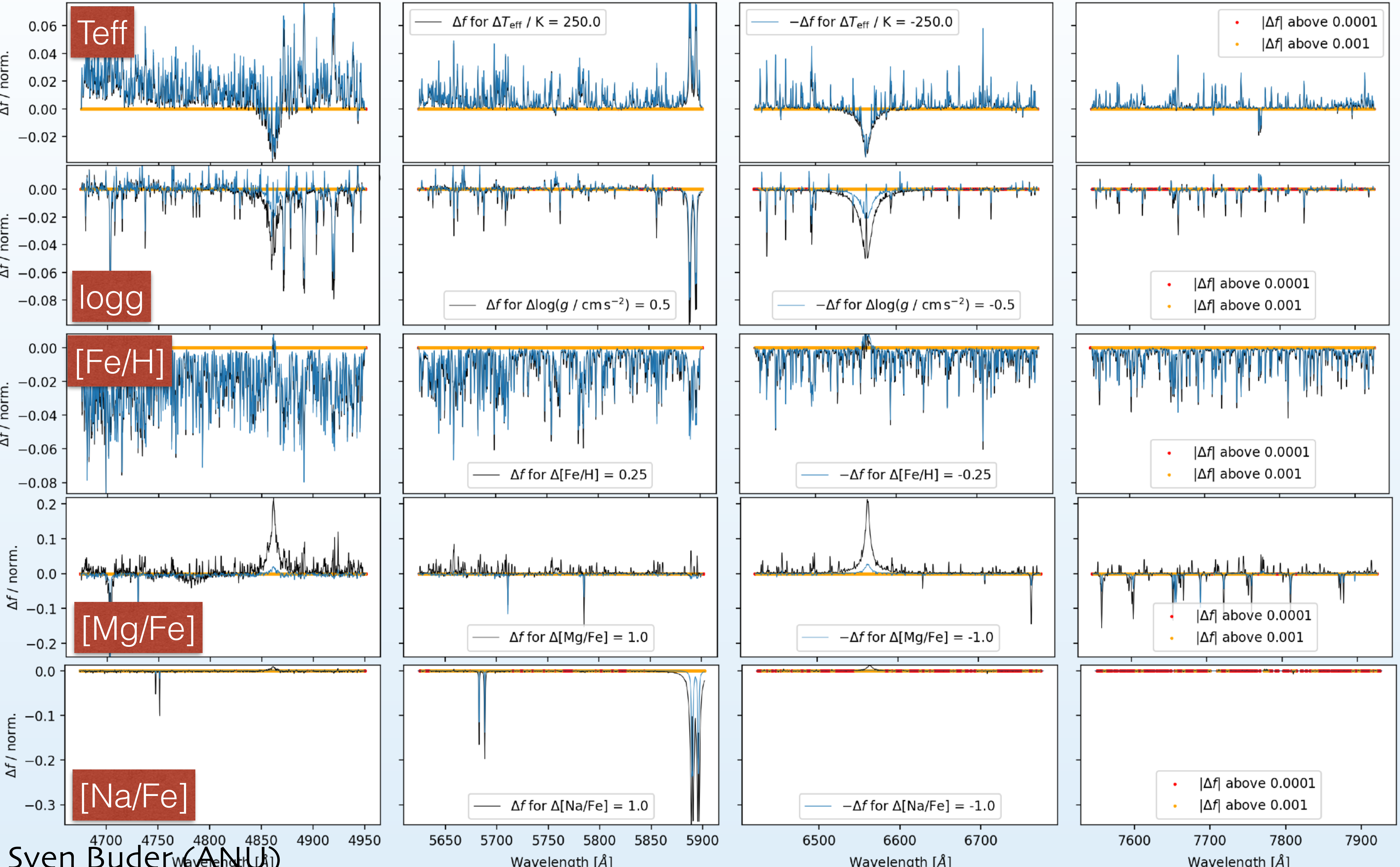
—> Feed these into neural network to interpolate fast

Simultaneous self-consistent abundance fits



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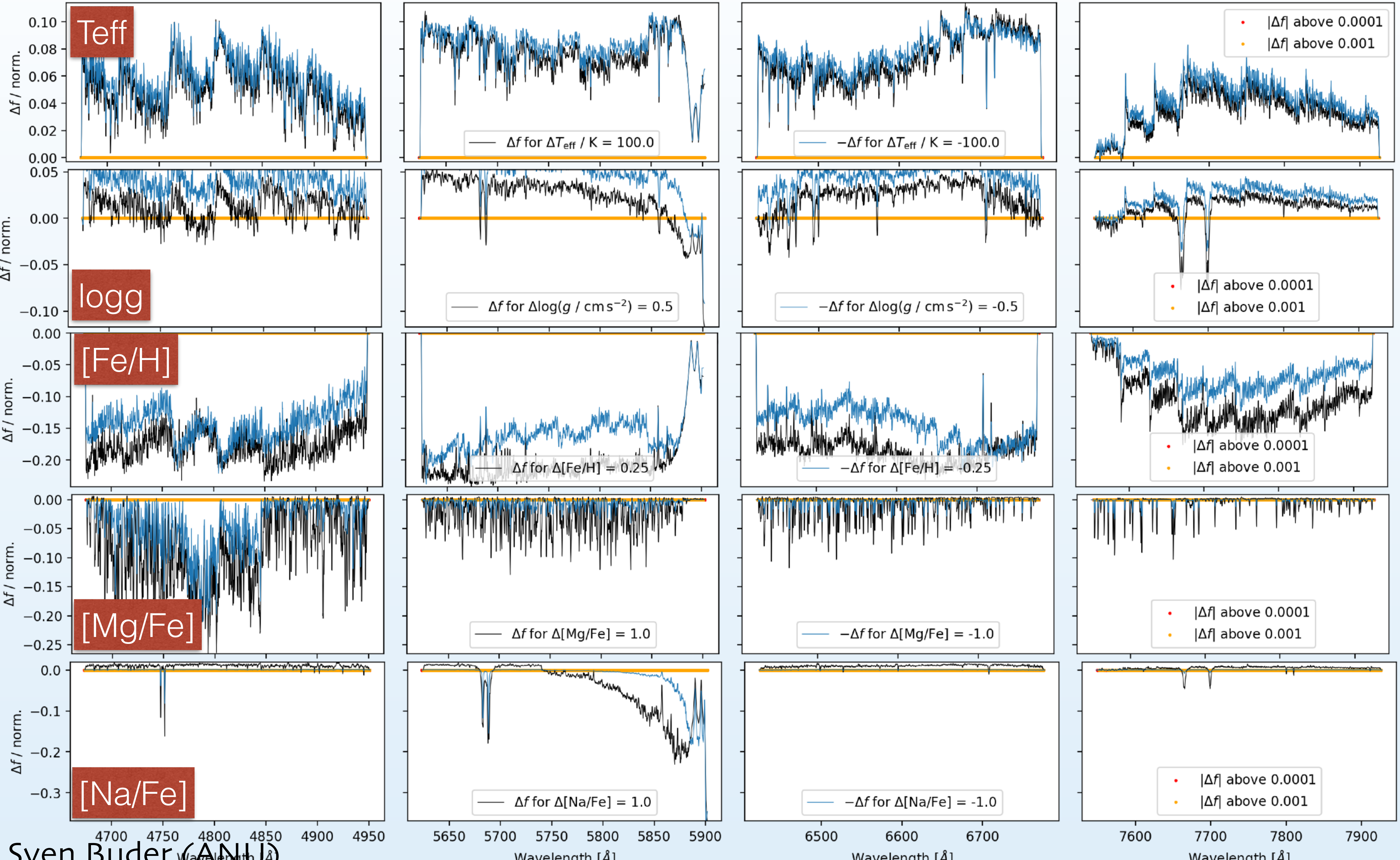
Does this also work for cool dwarfs?



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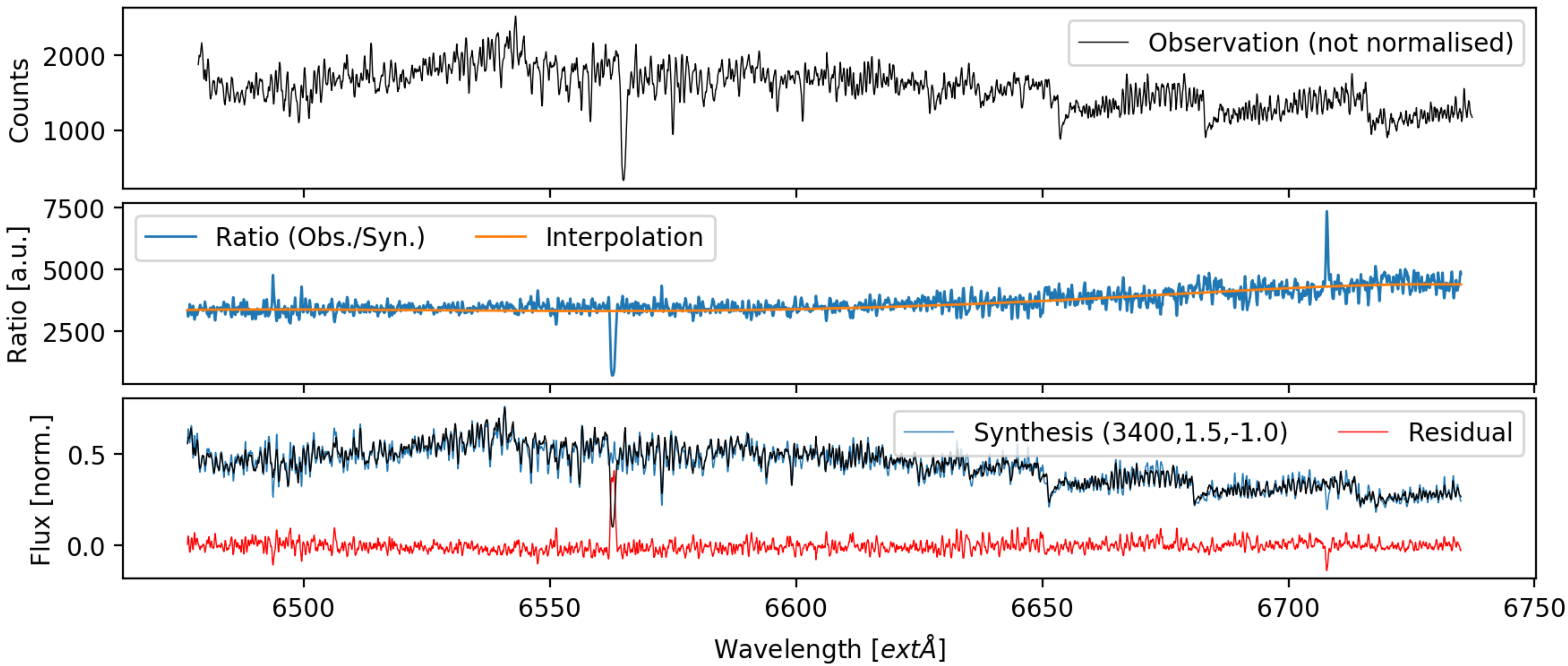
How can we best normalise continua?



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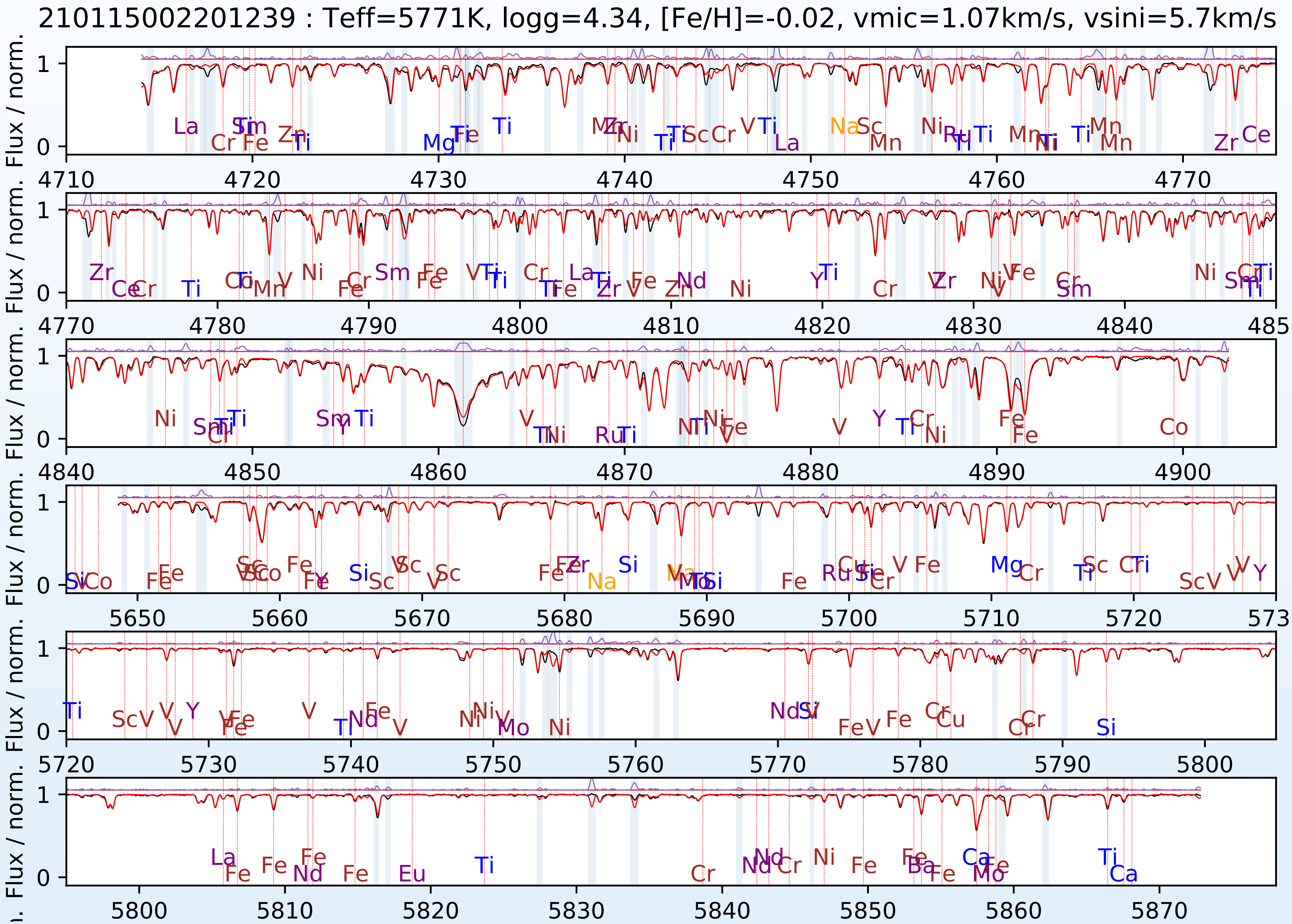
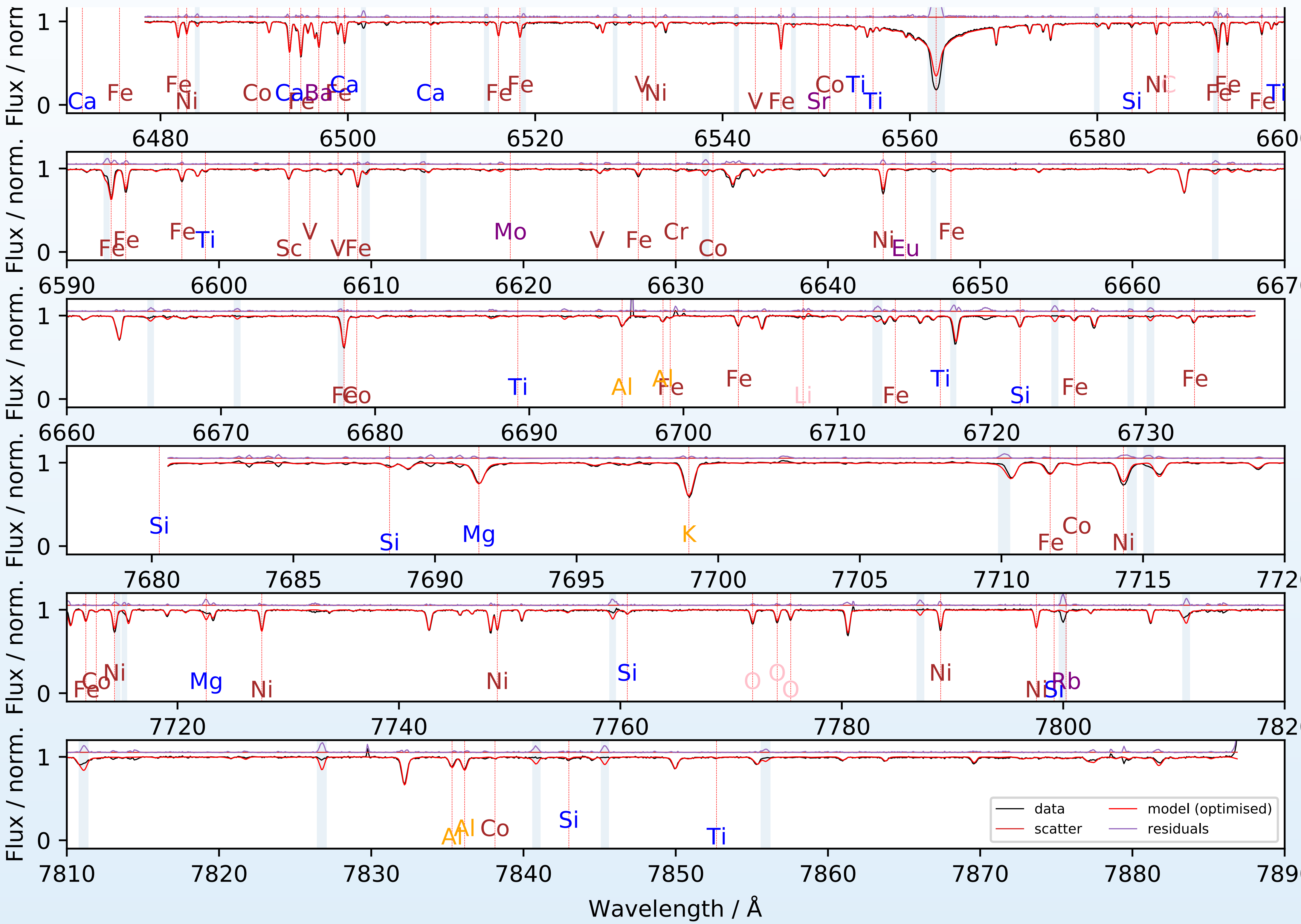
Use as much as we can from spectra



Use as much as we can from spectra



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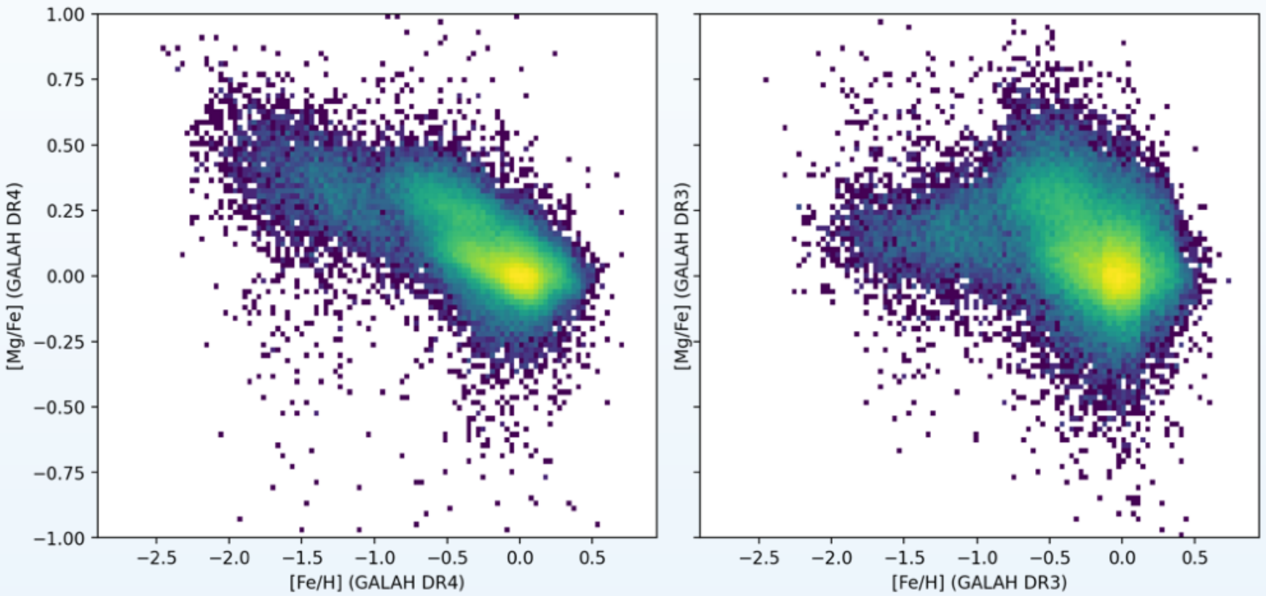
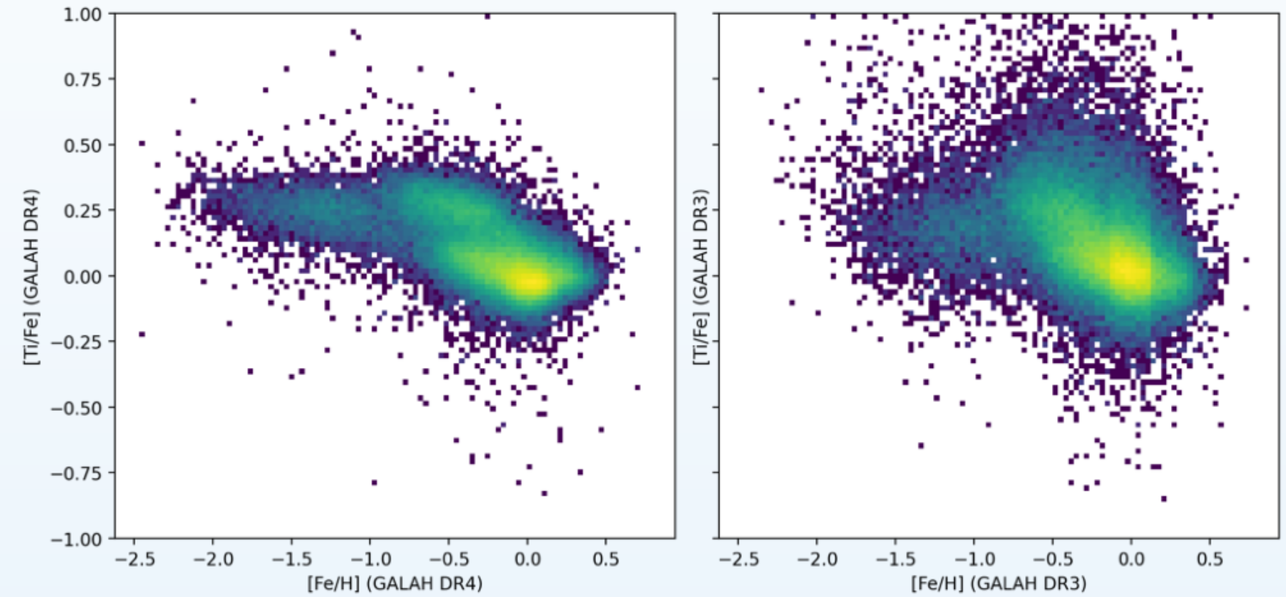
How well does it work?

GALAH DR4 (left) vs. GALAH DR3 (right)

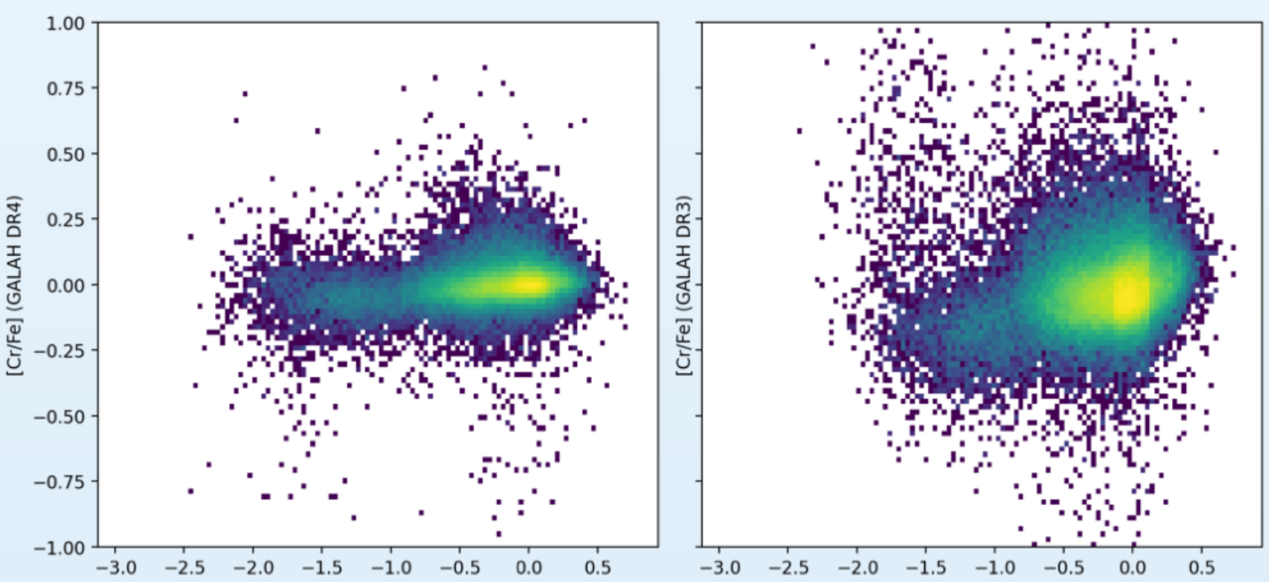
[Fe/H] vs. [Mg/Fe]



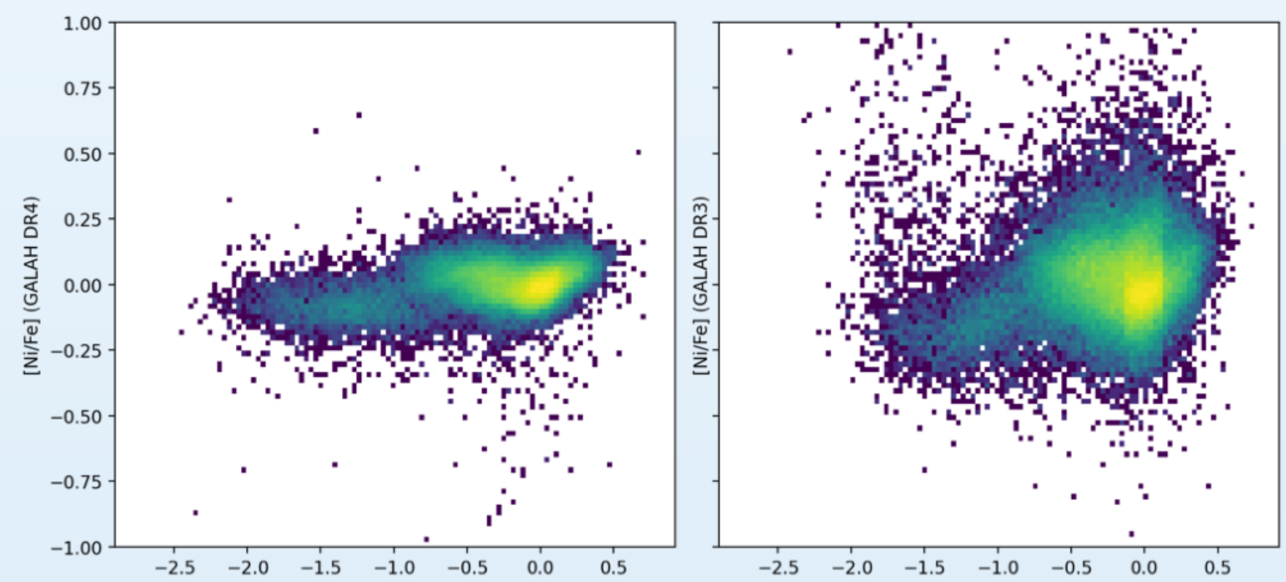
[Fe/H] vs. [Ti/Fe]



[Fe/H] vs. [Cr/Fe]



[Fe/H] vs. [Ni/Fe]



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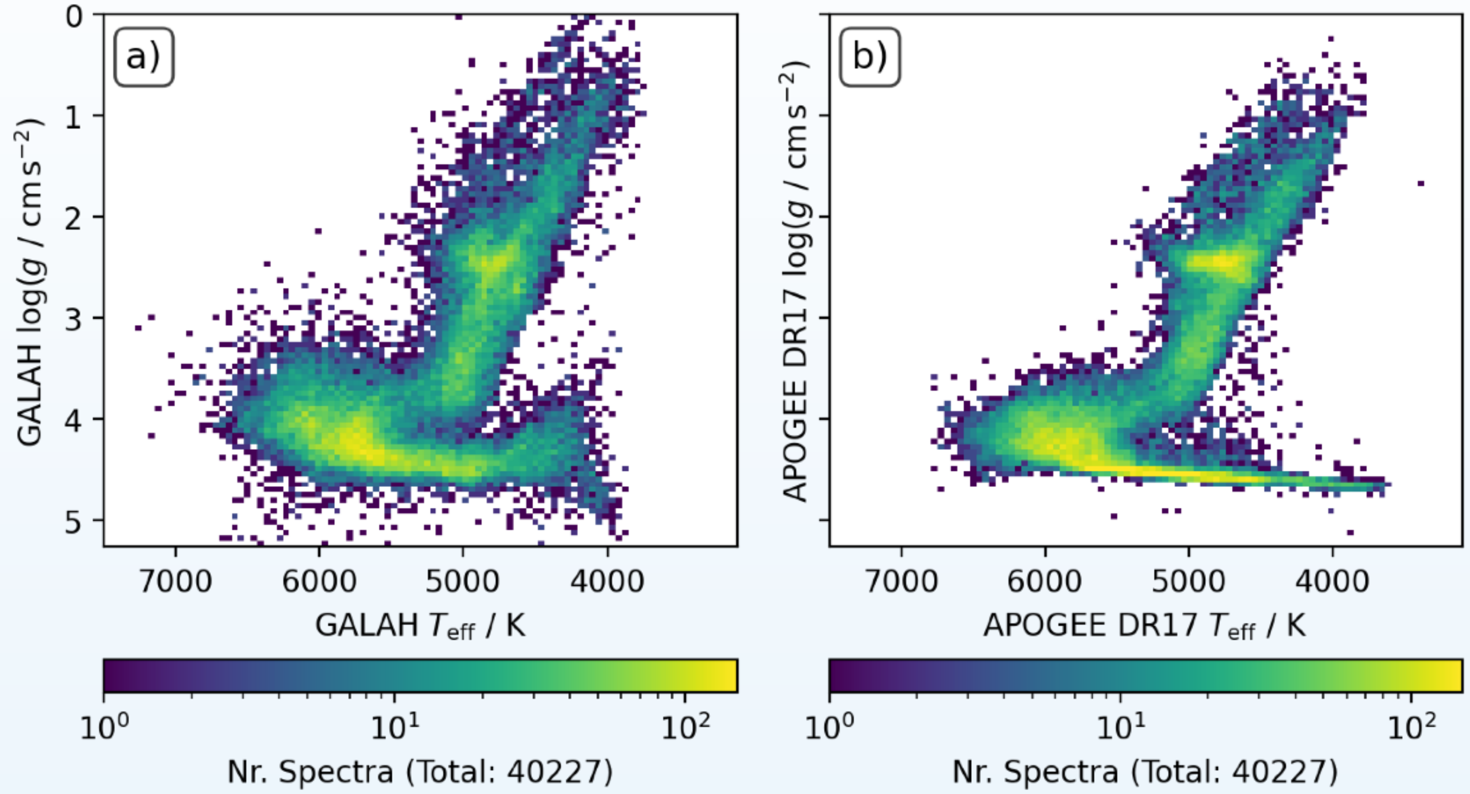
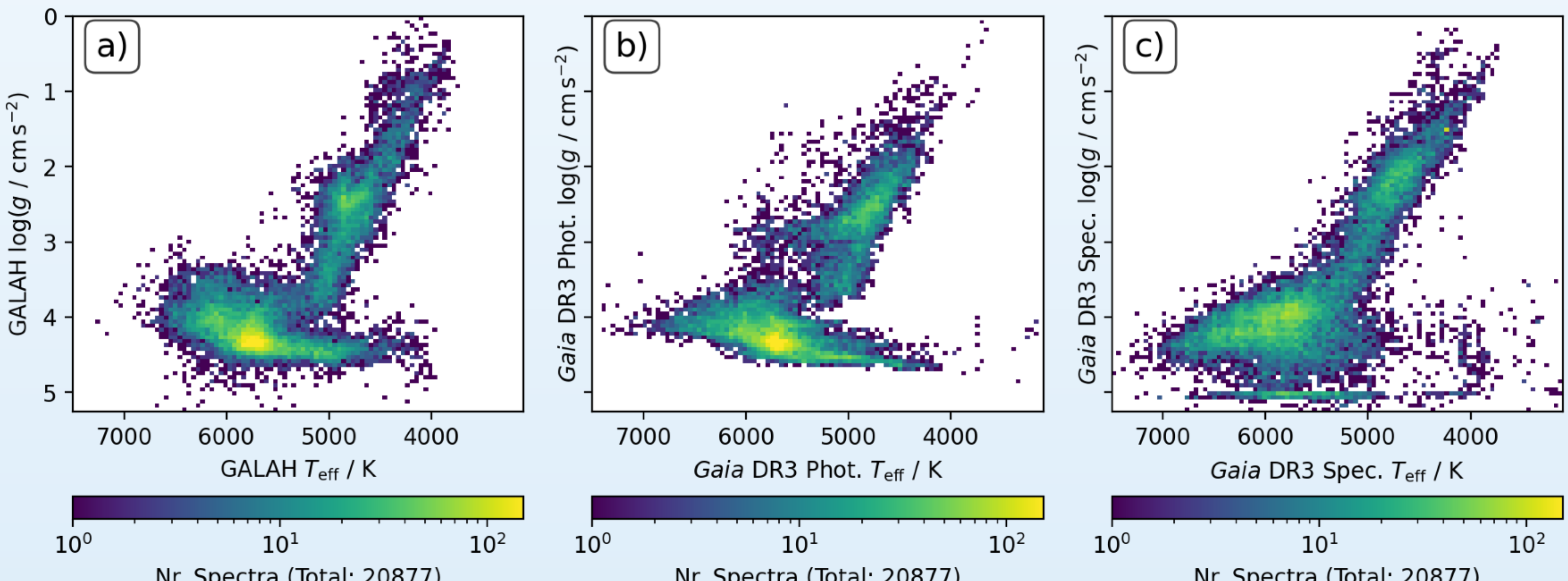
HRD: GALAH DR4 (Preliminary) vs. APOGEE DR17 vs. Gaia DR3





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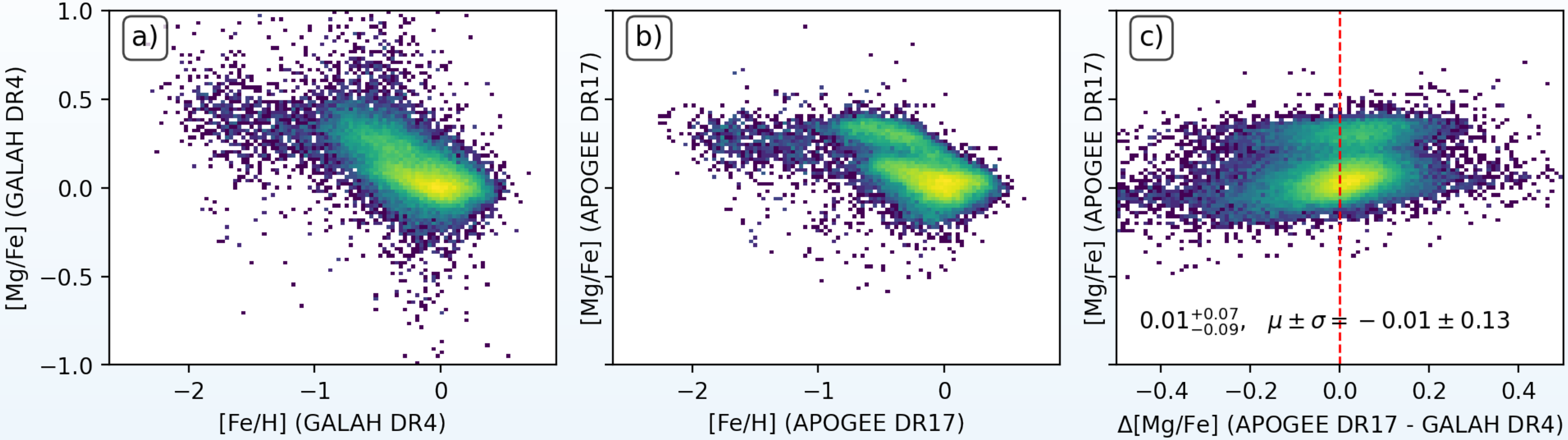
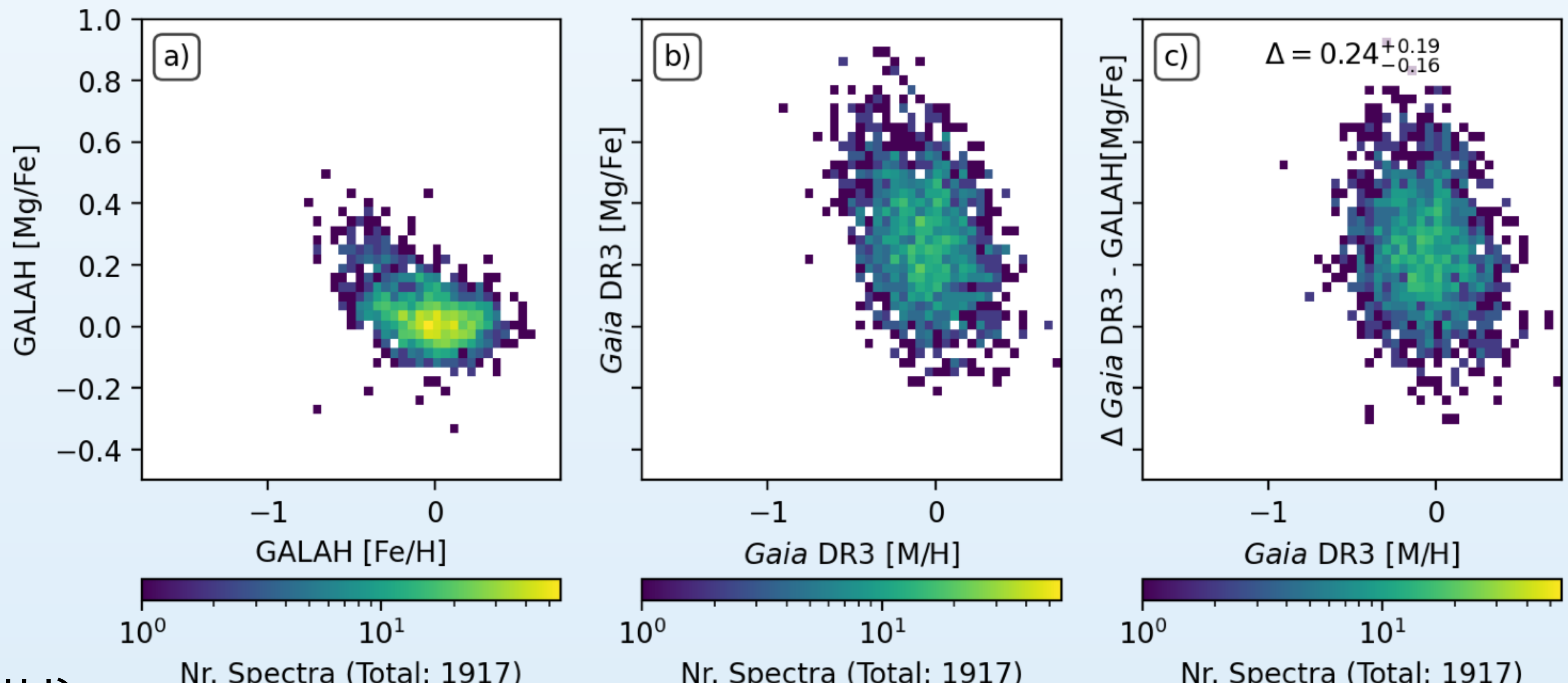
[Mg/Fe]: GALAH DR4 (Preliminary) vs. APOGEE DR17 vs. Gaia DR3





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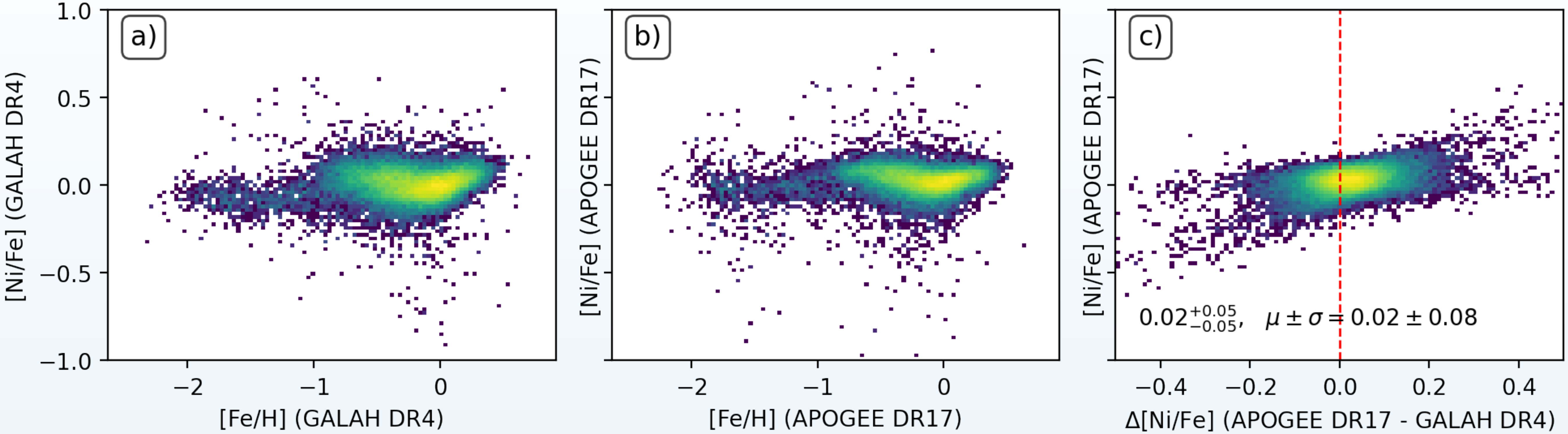
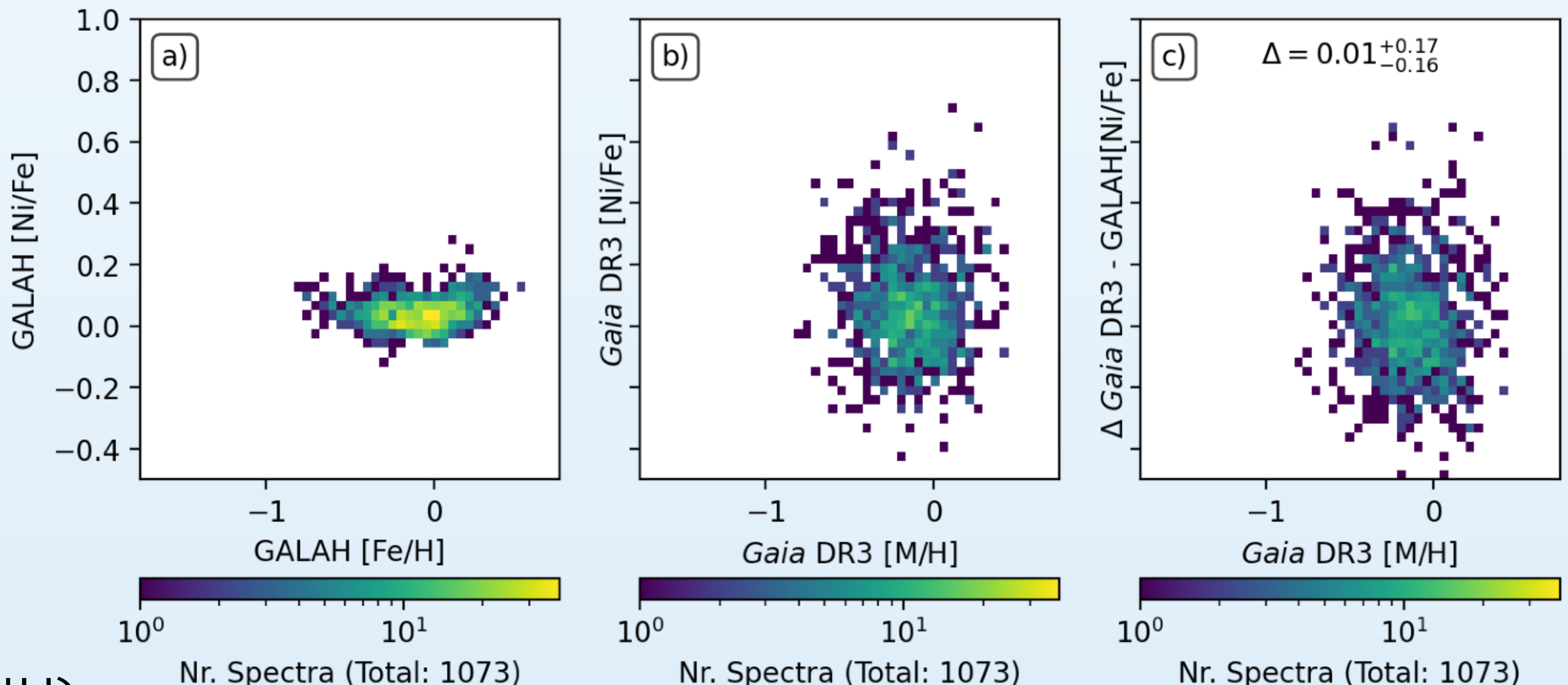
[Ni/Fe]: GALAH DR4 (Preliminary) vs. APOGEE DR17 vs. Gaia DR3





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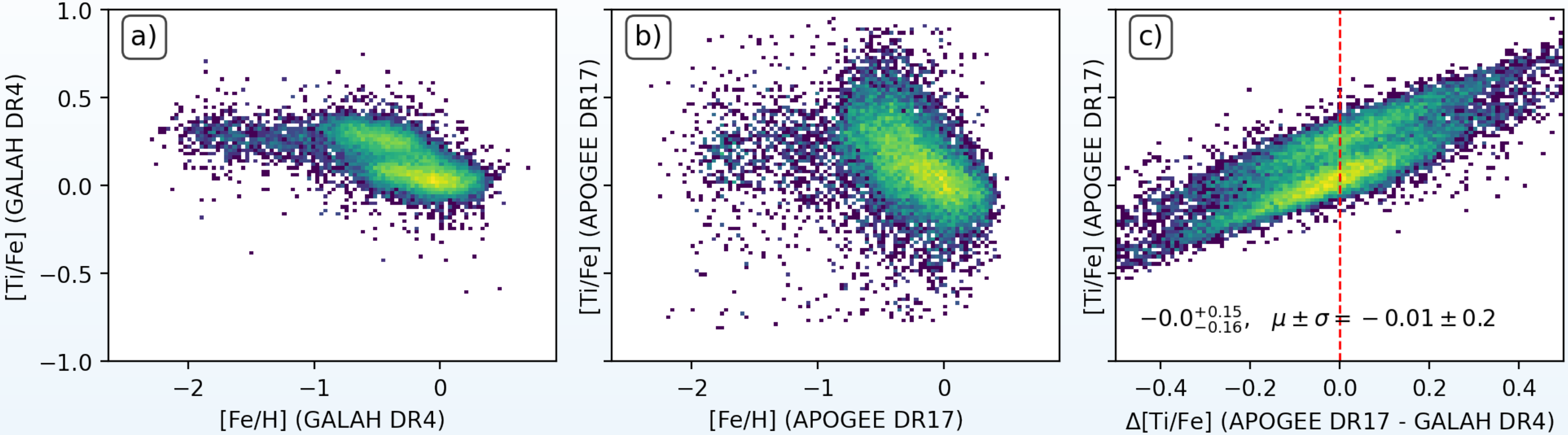
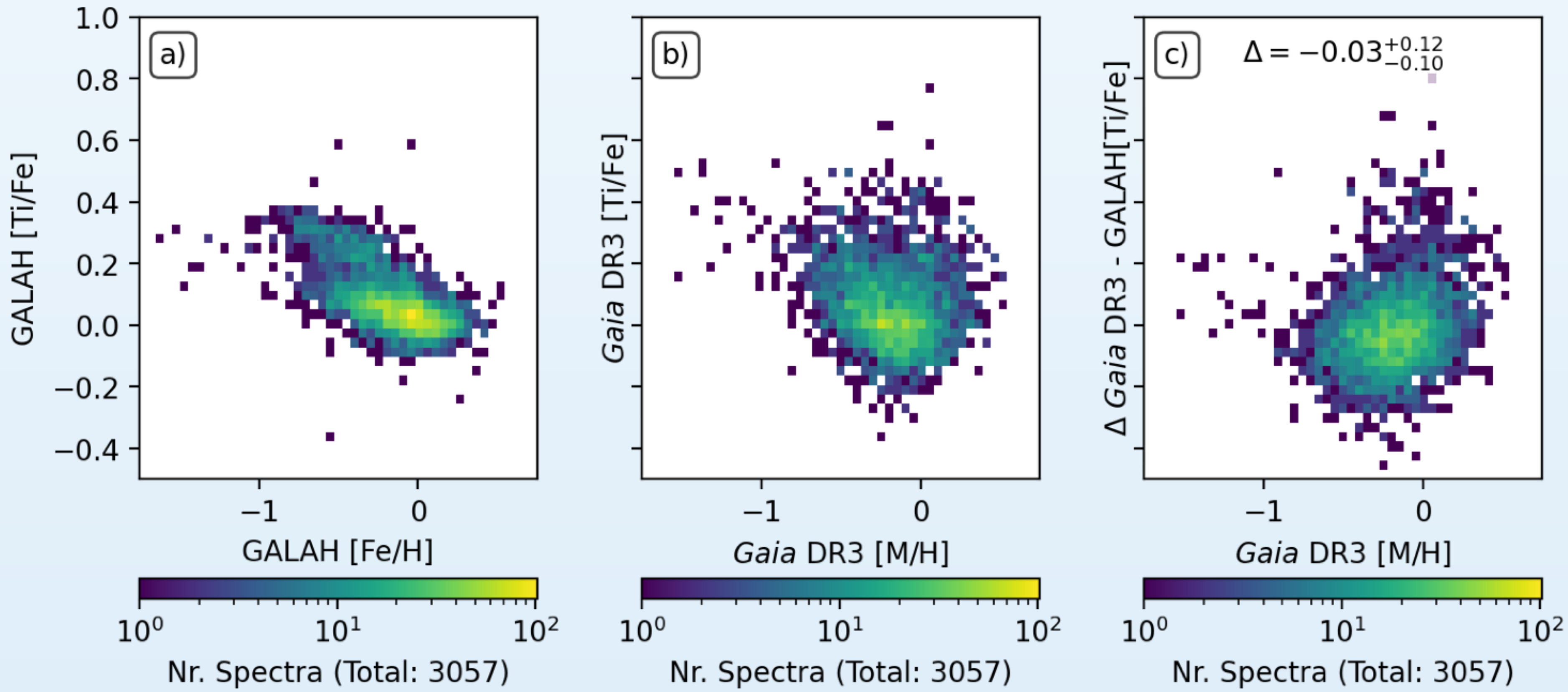
[Ti/Fe]: GALAH DR4 (Preliminary) vs. APOGEE DR17 vs. Gaia DR3





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CNO abundances

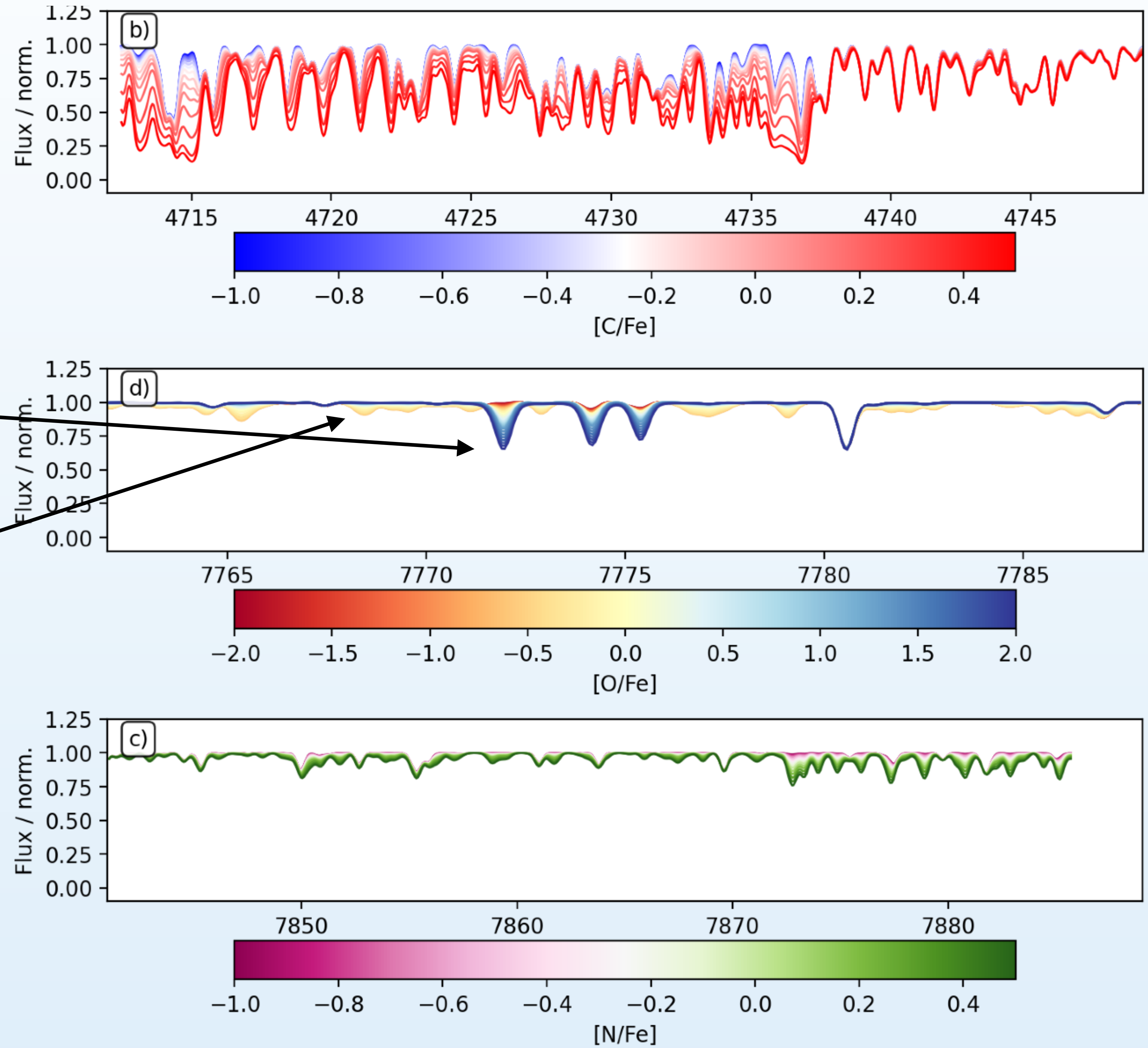
Atomic CI 6588
for warm stars

Molecular C_2, CN

Atomic OI 7772-7775

Indirect through
molecular equilibrium (CO)

Molecular CN



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CNO abundances