ASTR 511

Galactic Astronomy

Lecture 08

Chemical Cartography

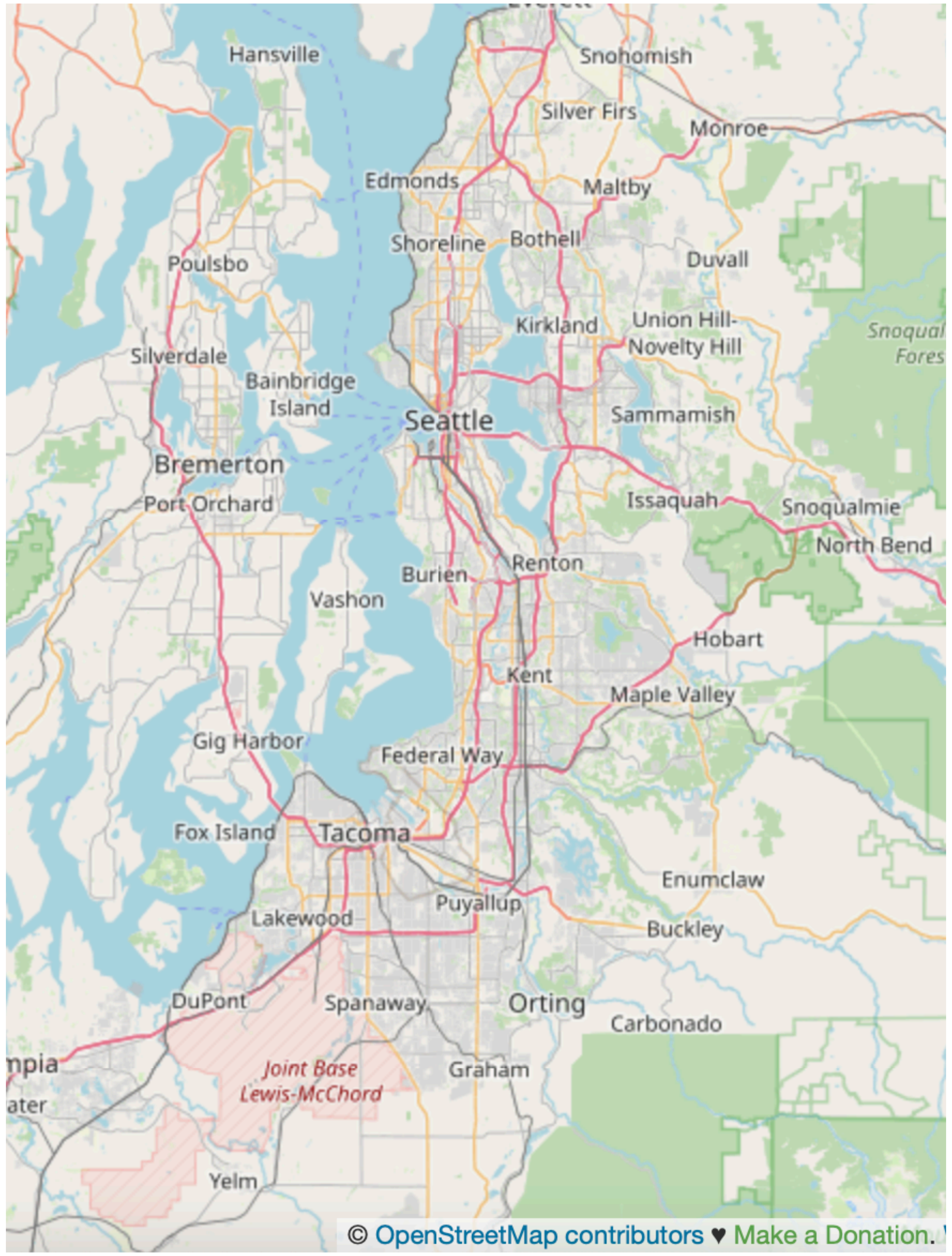
Prof. James Davenport (UW)

Winter 2023

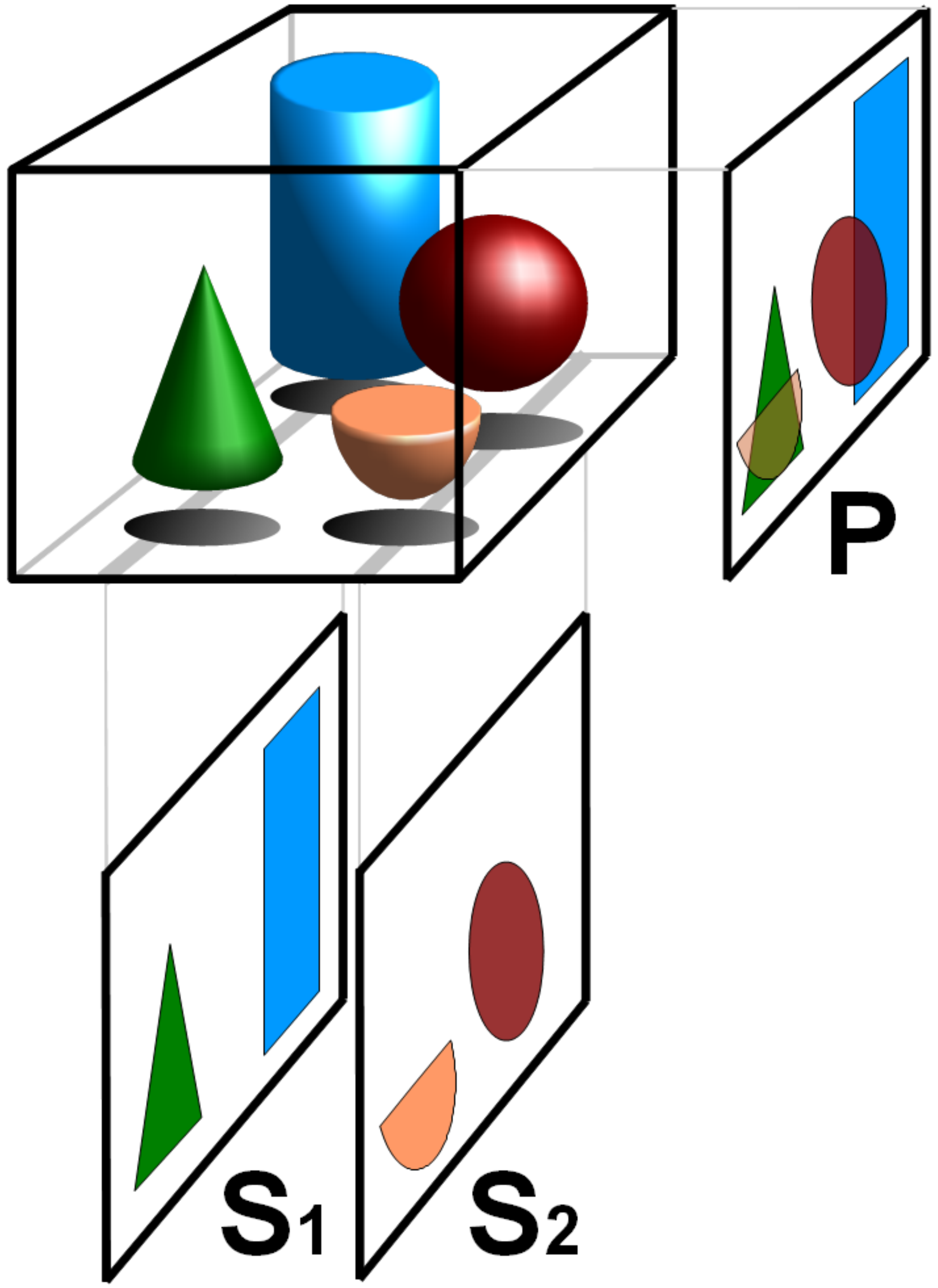
Cartography

Tabula Rogeriana (1154) Muhammad al-Idrisi

Cartography versus Tomography



openstreetmap.org



https://commons.wikimedia.org/wiki/File:TomographyPrinciple_Illustration.png

Both are tools in “Galactic Archeology”

This is another shockingly deep field of study

i.e. we'd need *several* lectures to do it justice

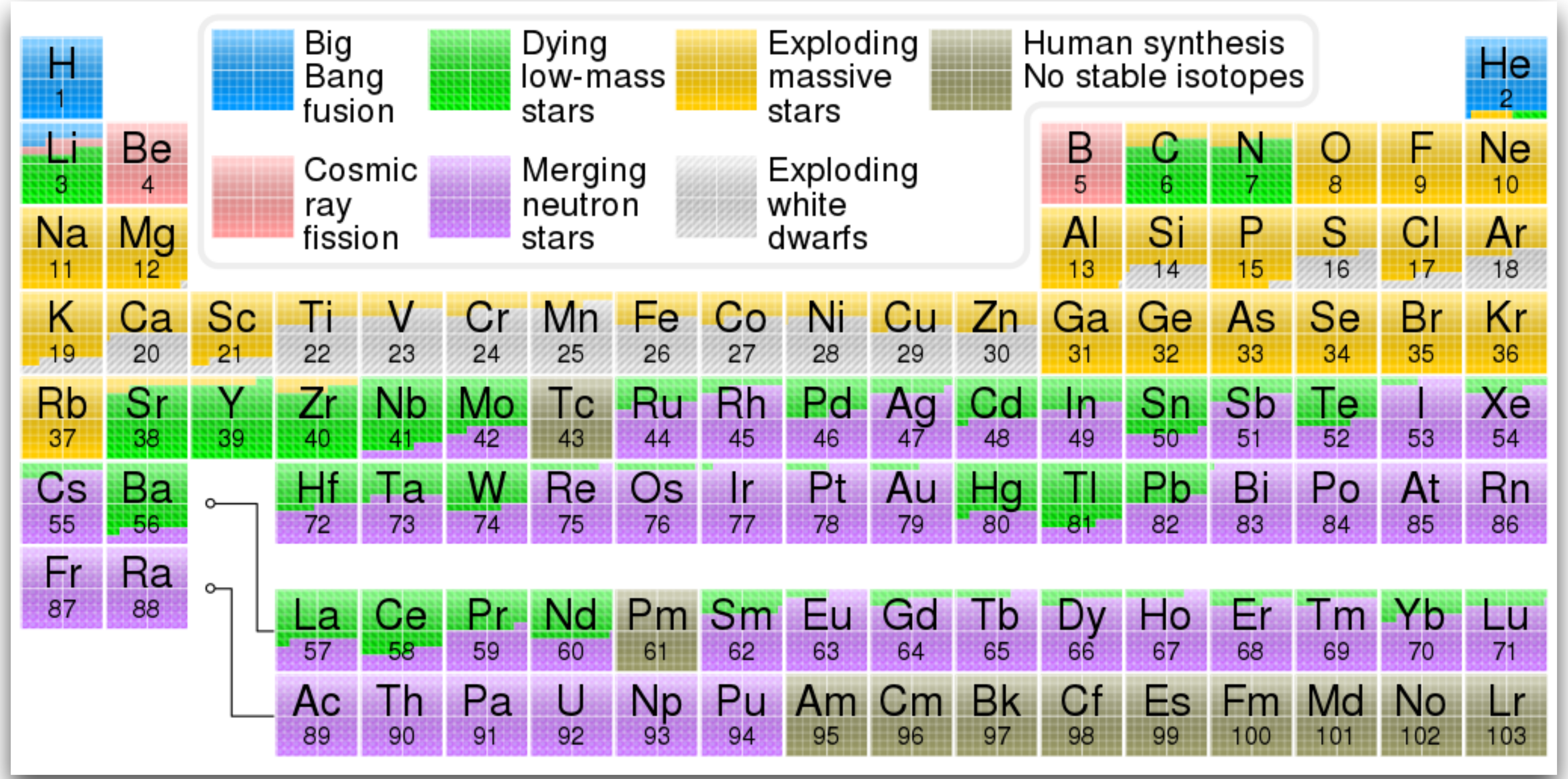
Instead: we'll try to keep to 1 lecture & HW3

Basic Story: Age -> Metallicity

- In the beginning there were no metals (Pop III stars)
- Then there were few metals (Pop II stars)
- Now there are increasingly more metals (Pop I stars)

- Stars burn H -> He, mess with other elements along the way (e.g. CNO)
- AGB stars generate s-process elements in shell layers of fusion
- SNe quickly produce r-process elements

Basic Story: Age -> Metallicity



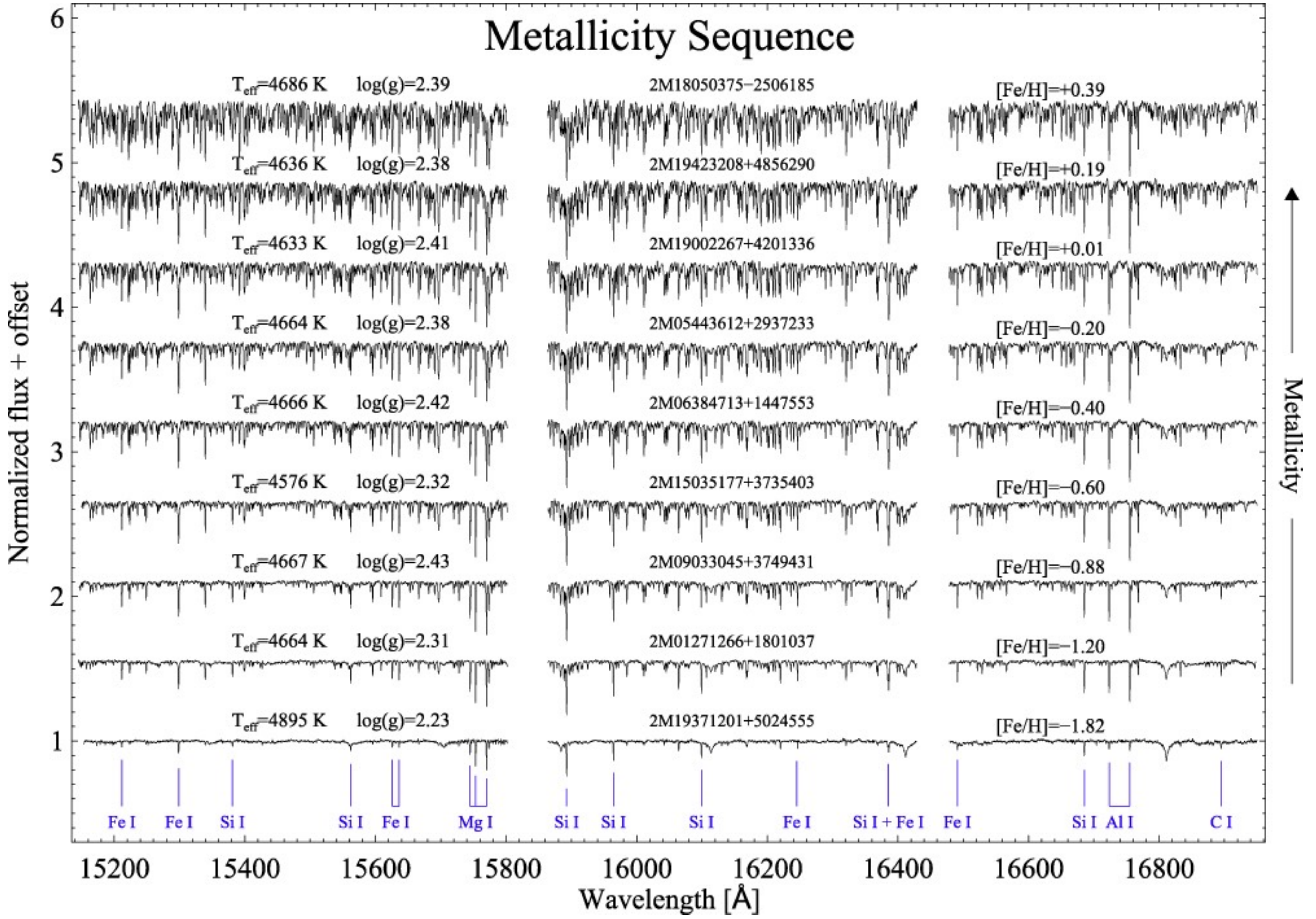
https://commons.wikimedia.org/wiki/File:Nucleosynthesis_periodic_table.svg

Basic Story: Age -> Metallicity

- Metals, typically approximated as **[Fe/H]**, indicate age!
- As we've discussed, key to describing origin stories of every part of the Galaxy, young vs. old
- Affects stellar evolution (e.g. opacities, gas cooling, etc)
- Entire galaxies shown to have bulk metallicities, impact Star Formation, IMF

Basic Story: Metallicity

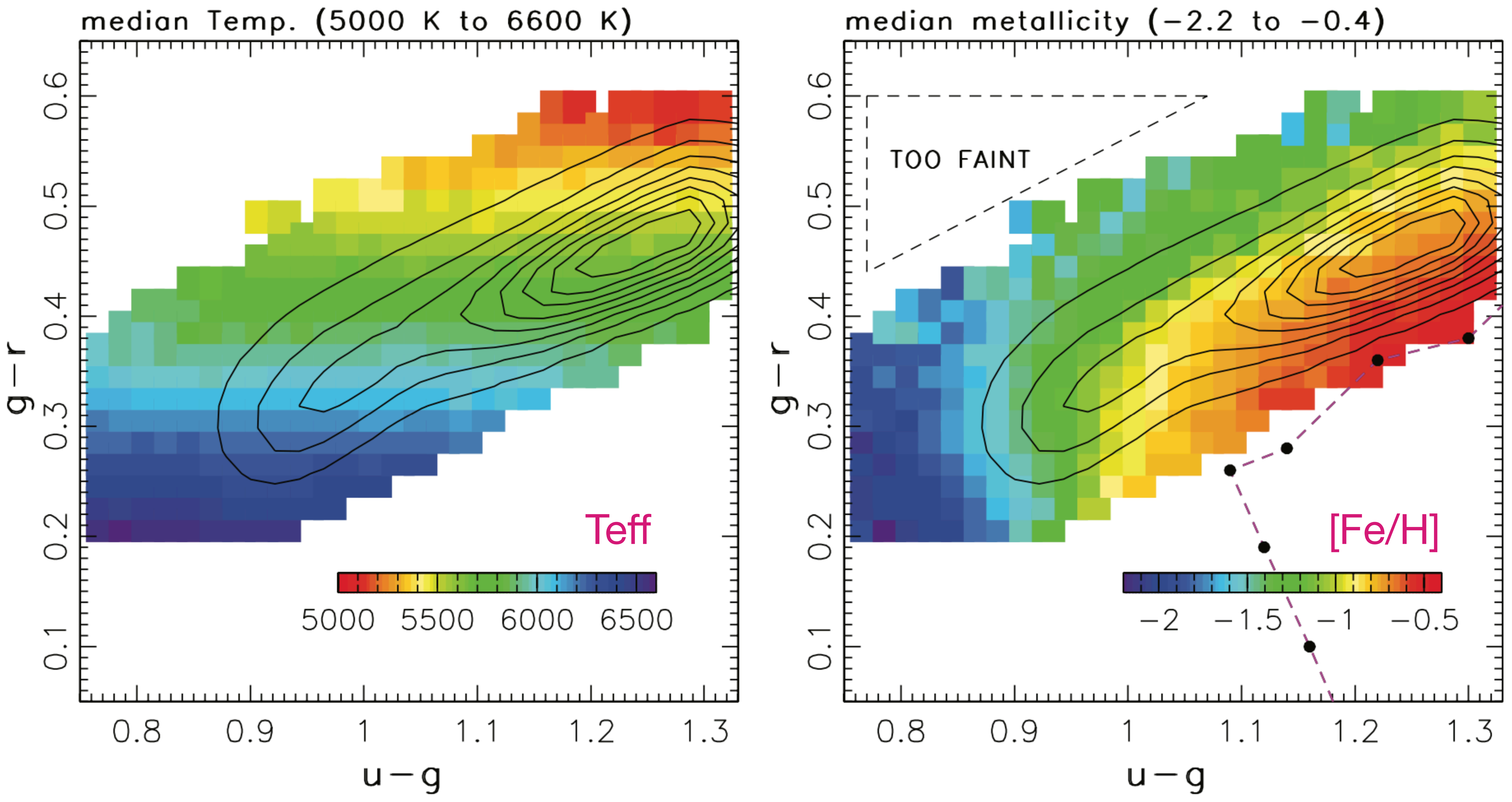
- Typically summed up as [Fe/H], i.e. the log ratio of Fe/H *relative* to the solar amount
  - Also abundances of individual elements are studied, as well as groups (e.g. [α/Fe])
- Primarily determined via spectroscopy, modeling atomic absorption lines
  - High resolution VERY helpful



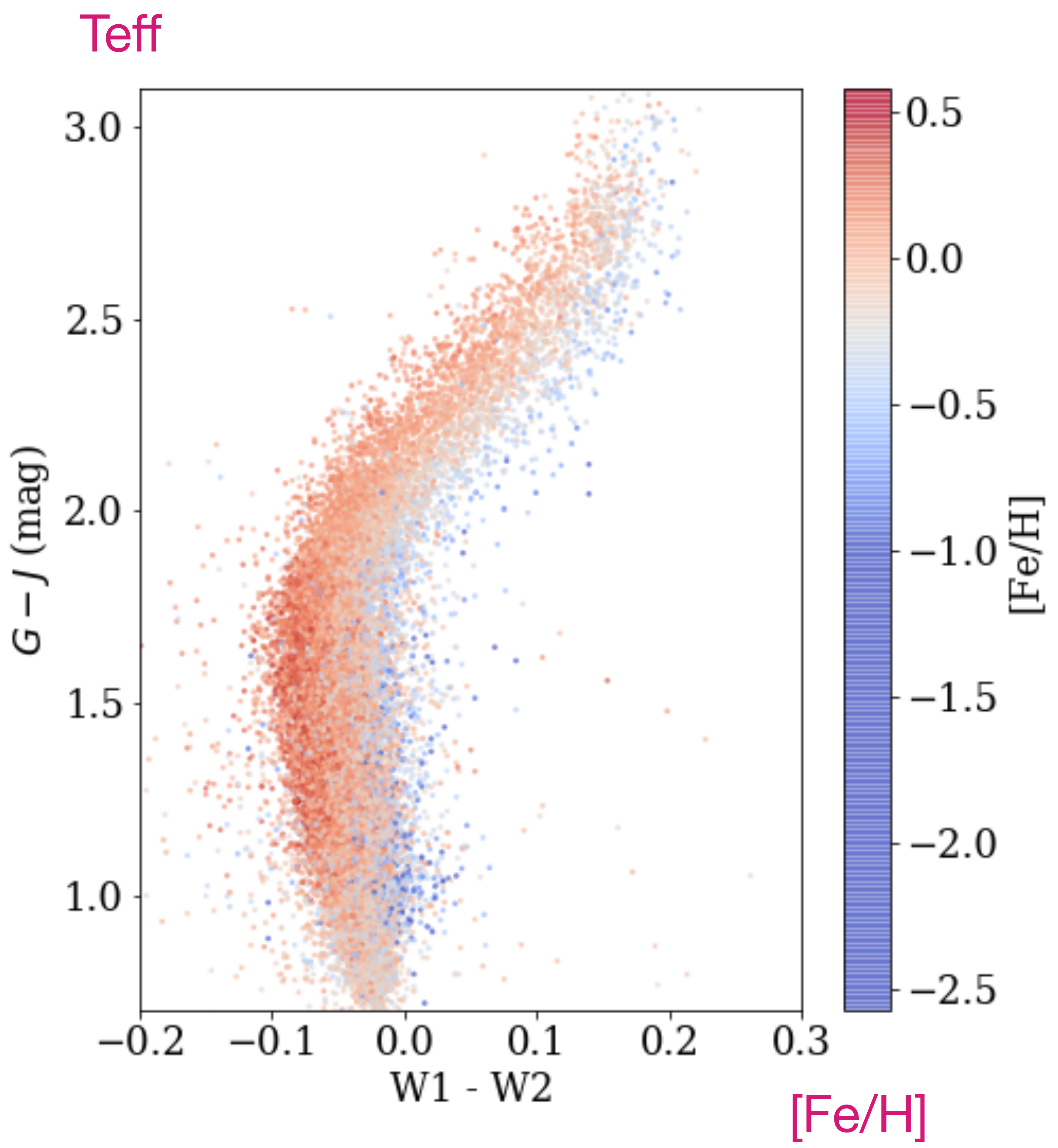
Majewski+2017 (APOGEE)

Method 1. Photometric Metallicity

- Amazing for statistics with big surveys (hello: LSST!)



[Ivezic+2008]

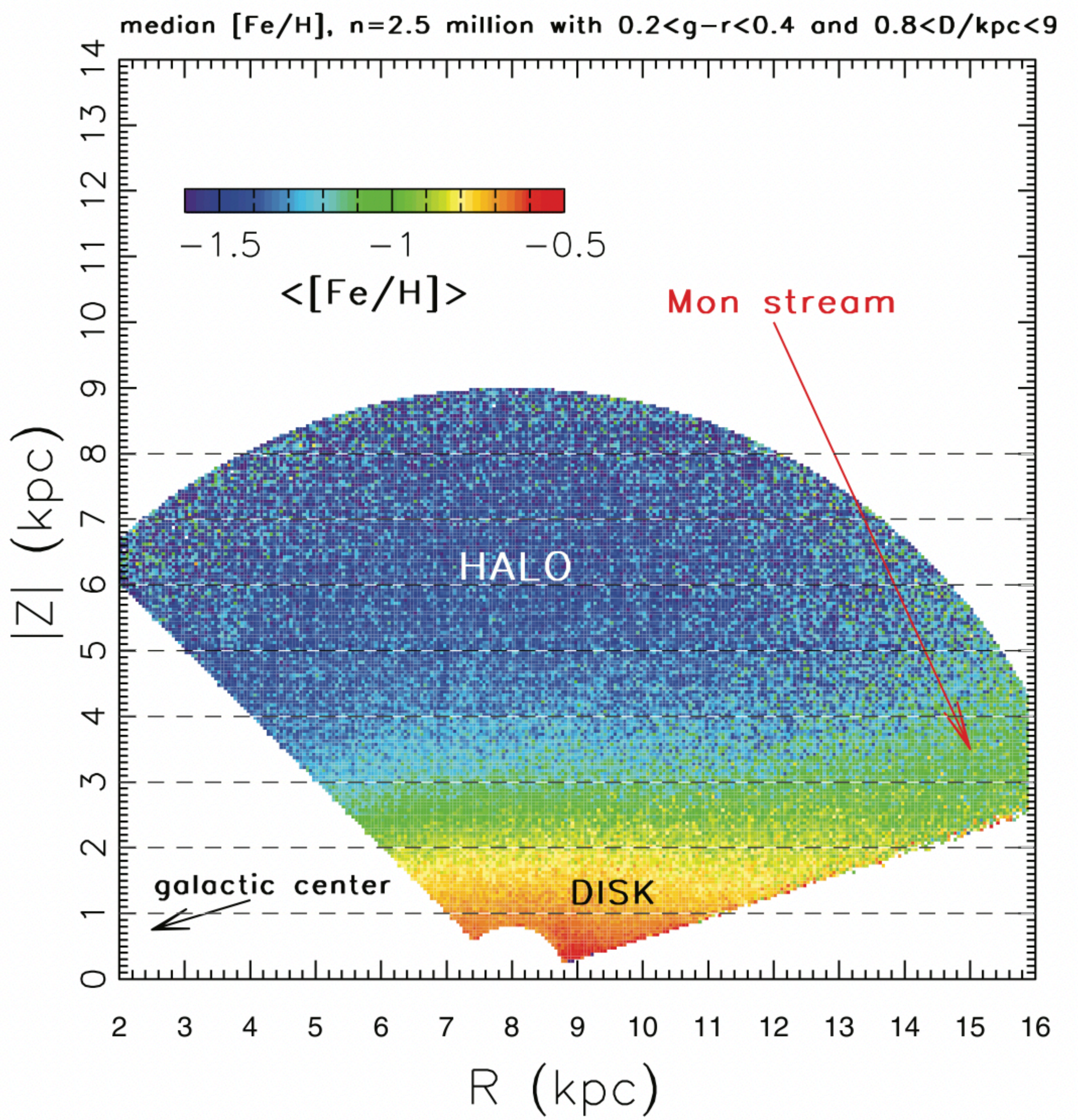


[Davenport & Dorn-Wallenstein (2019)]

Method 1. Photometric Metallicity

- Amazing for statistics with big surveys (hello: LSST!)

- Doing this for hundreds of thousands (or even millions) of stars enables new studies of the composition of our galaxy!
- Take slices: Galactic Tomography
- Wonderful new term: chemical cartography



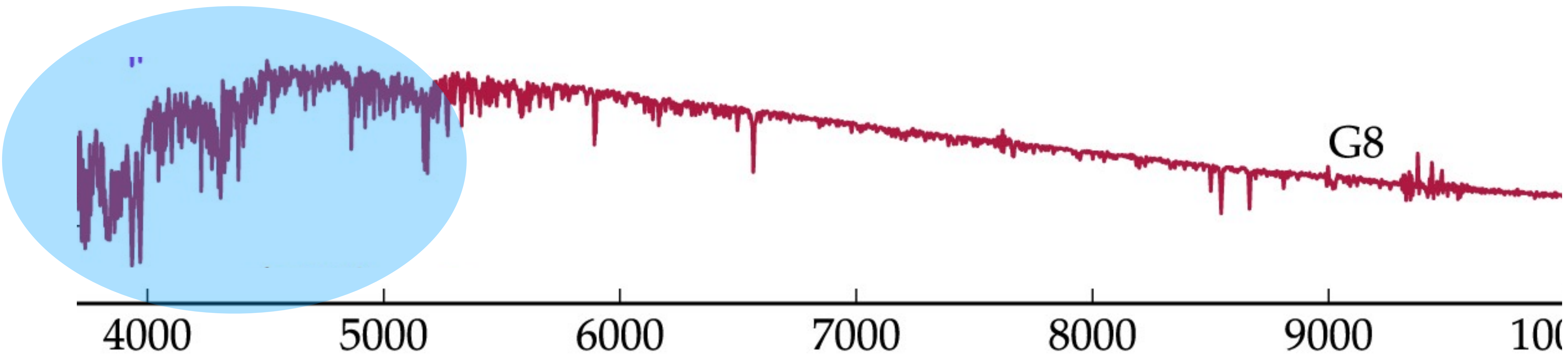
Ivezic+2008

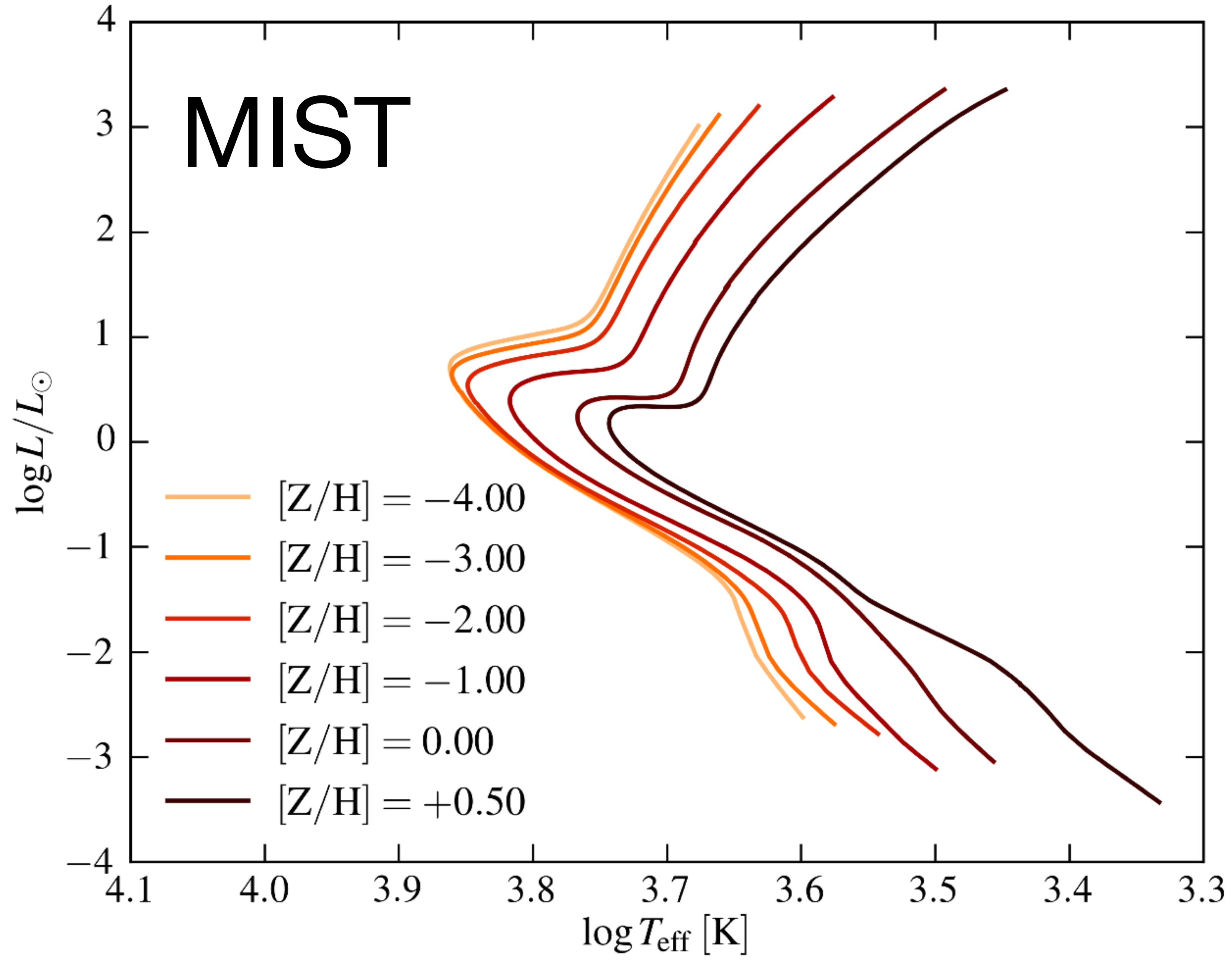
Method 1. Photometric Metallicity

- Amazing for statistics with big surveys (hello: LSST!)

- In general, metal-poor: bluer (hotter T_{eff})
  metal-rich, more lines, redder

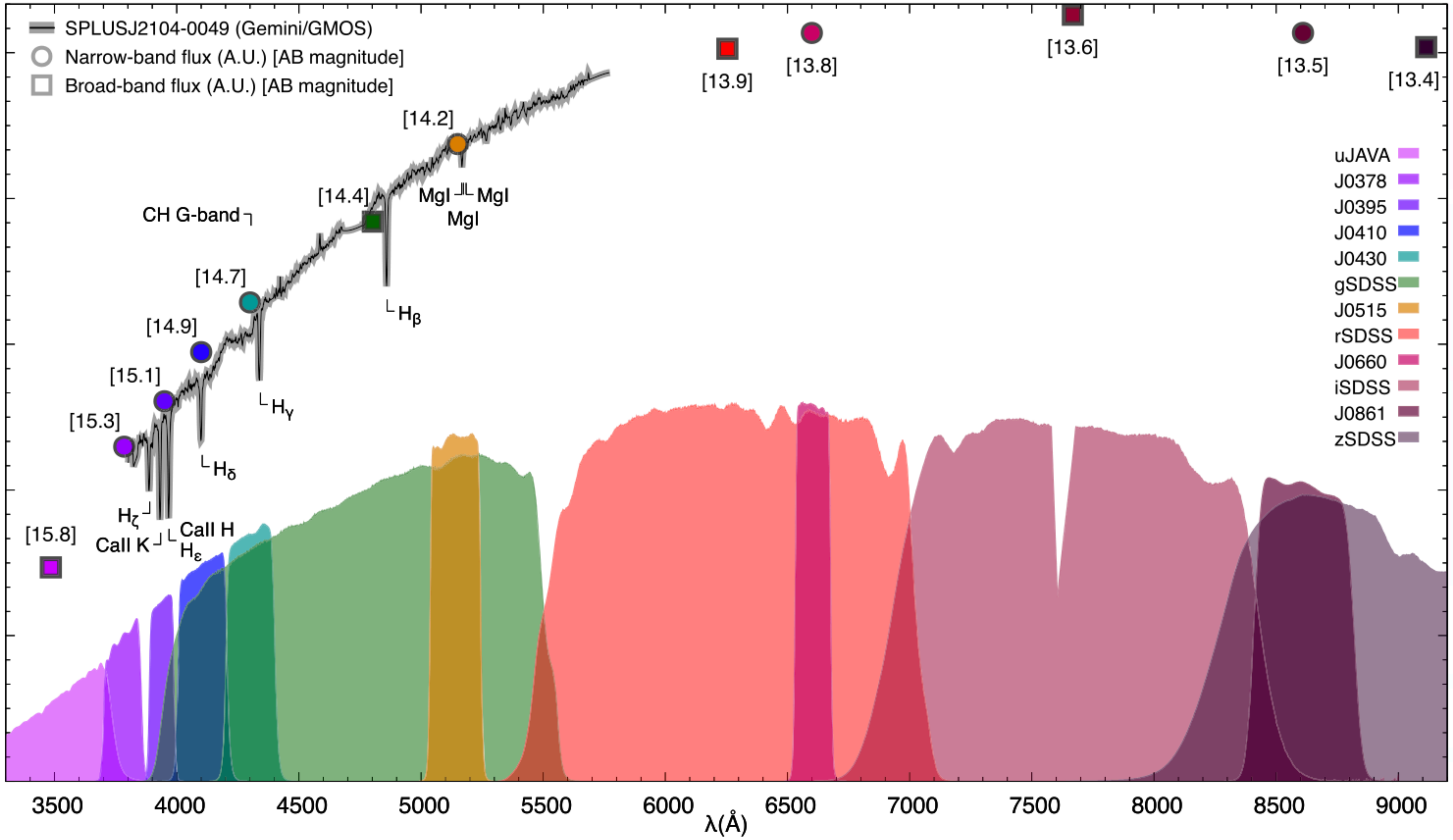
- Typically need blue (e.g. *u*-band) filters
  BUT, some sensitivity in the IR too





Method 2. Narrow Band Filters

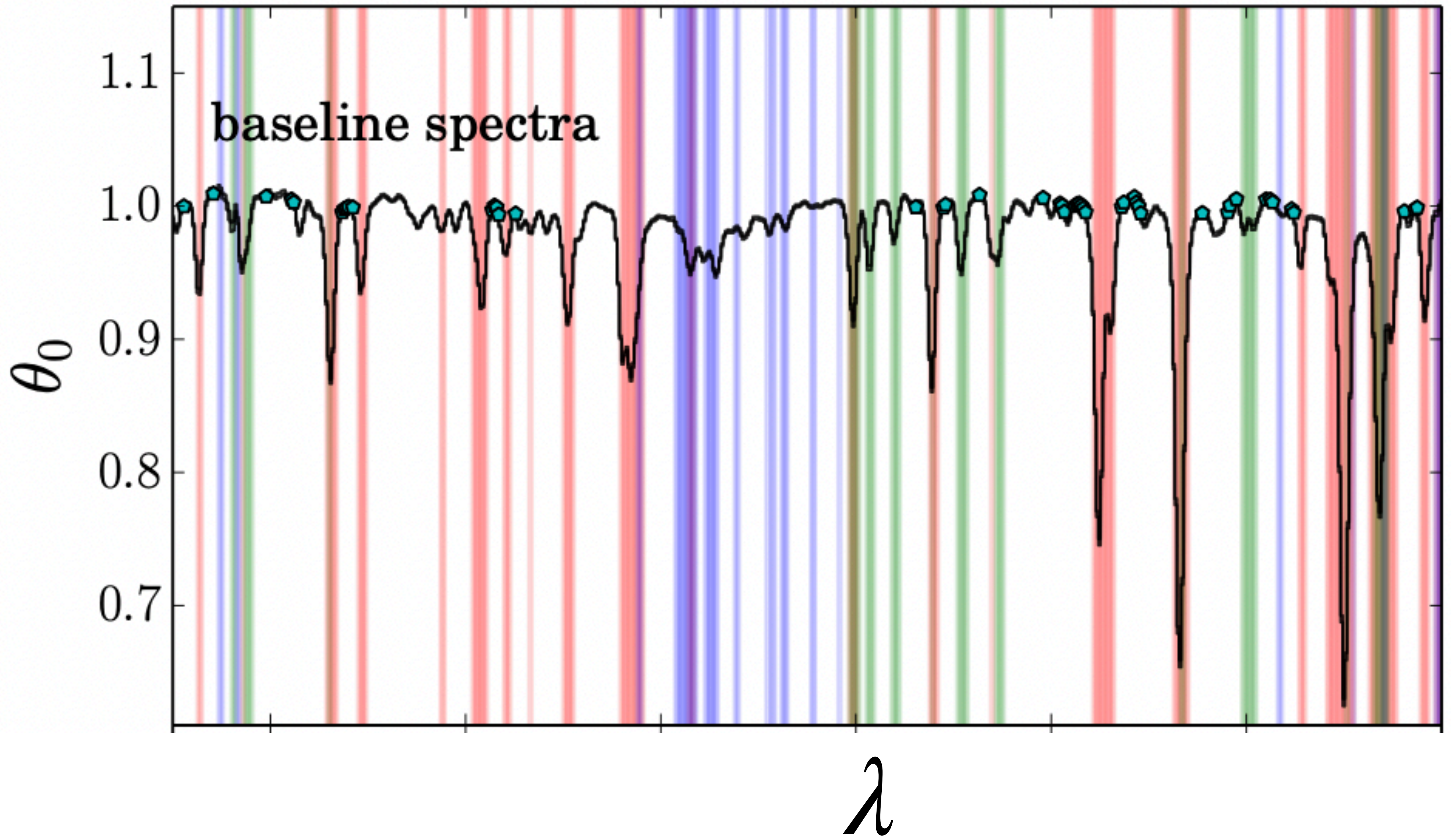
- Filters centered on spectral lines/features that are sensitive to specific elements
- Example: an "Ultra Metal-Poor Star" from S-PLUS
- **Not super popular (alas!) but long used/studied**
    - e.g. Strömgren filters!



Placco+2021

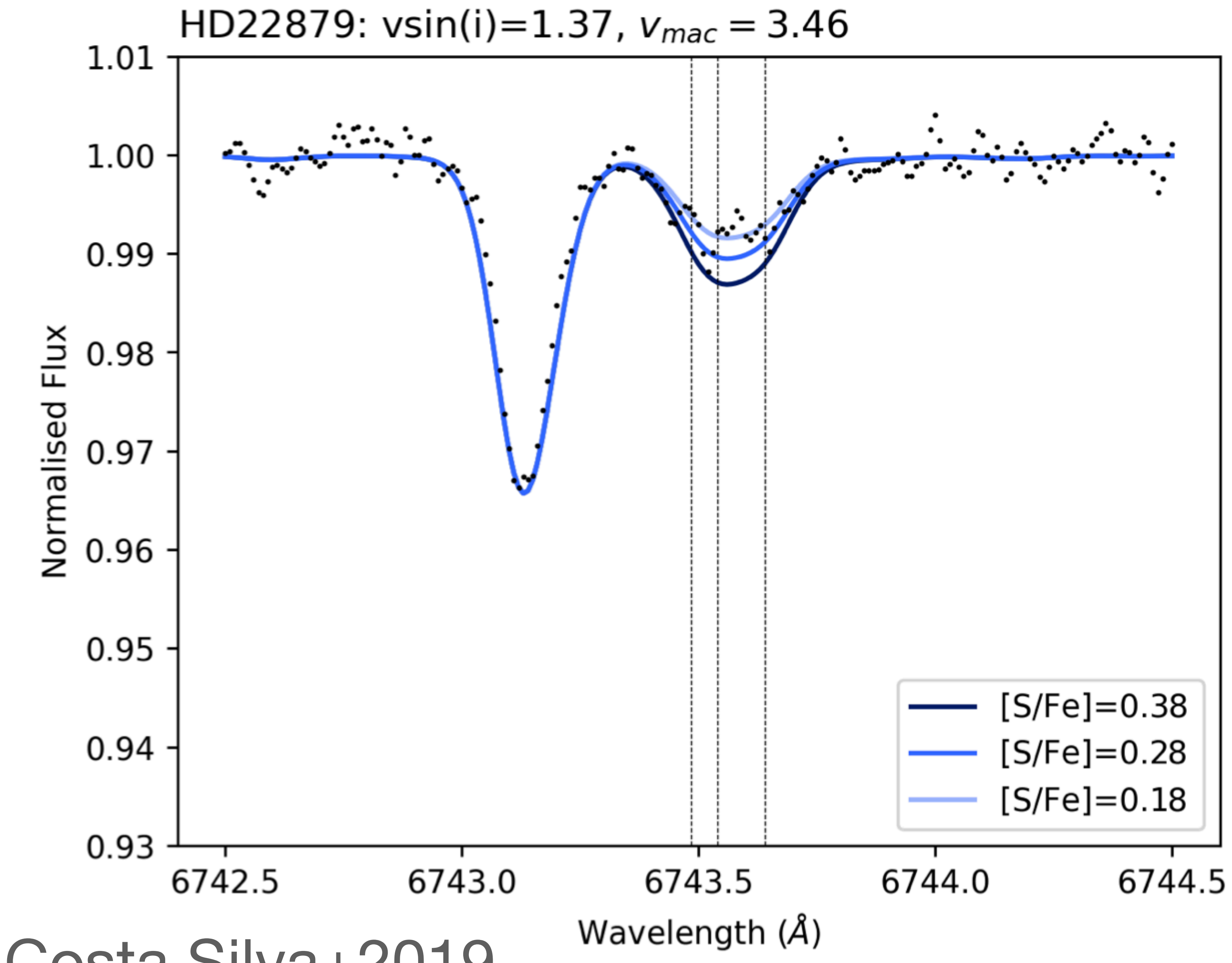
Method 3: Spectroscopy

- Can be done with high or low resolution (higher-res better, obviously)
- Trace bulk metallicity [Fe/H] or [M/H], esp. with low-res fairly easily
- Track individual element species (beware: complex stellar atmosphere and "spectral synthesis" modeling challenges!)
- Some rad new data-driven tools (e.g. The Cannon)



[Fe/H]
log g
Teff

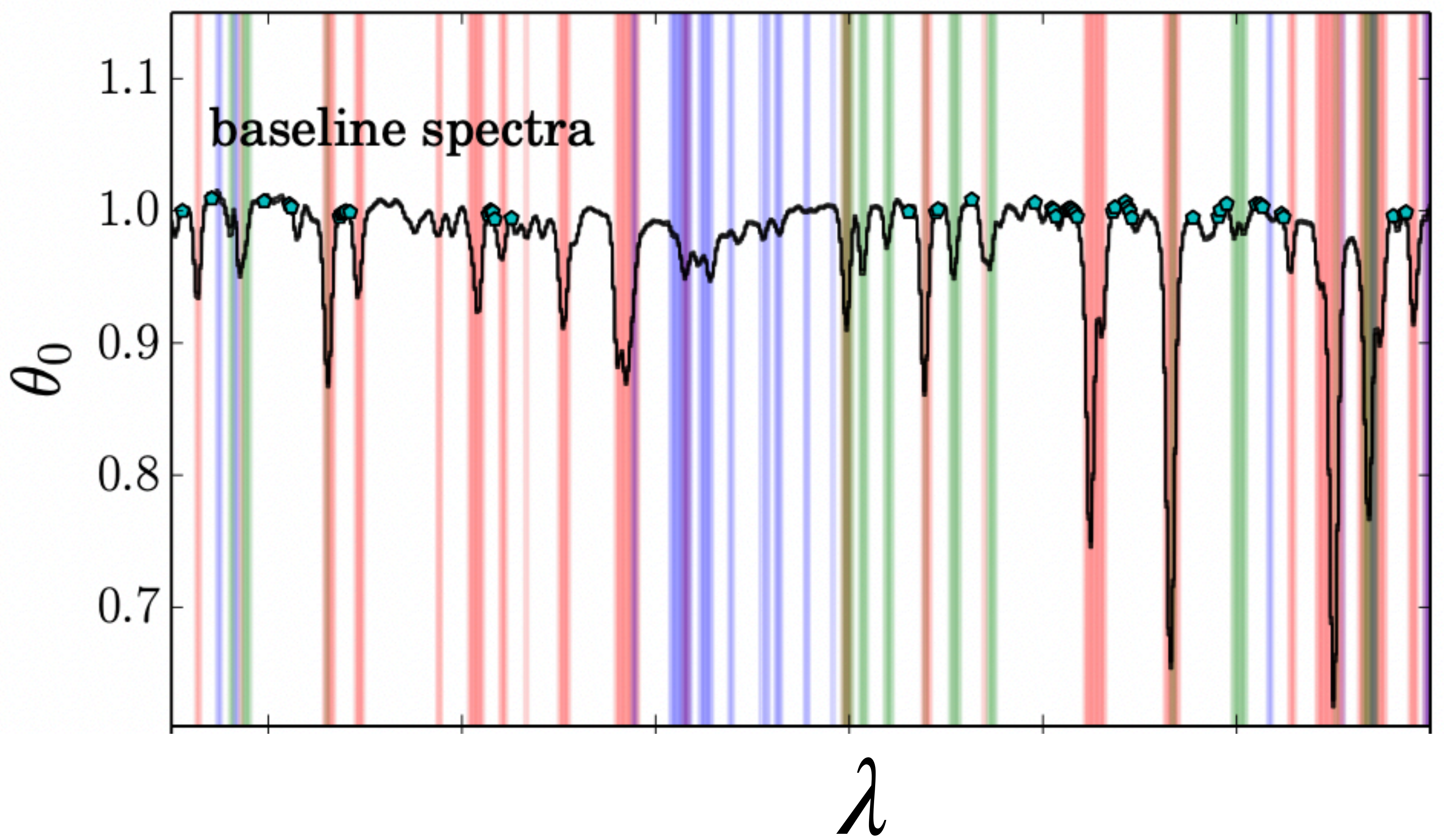
Ness+2015



Costa Silva+2019

Method 3: Spectroscopy

- We in the era of Spectroscopic Surveys!
  - SDSS (I-IV), APOGEE, GALAH, RAVE



[Fe/H]
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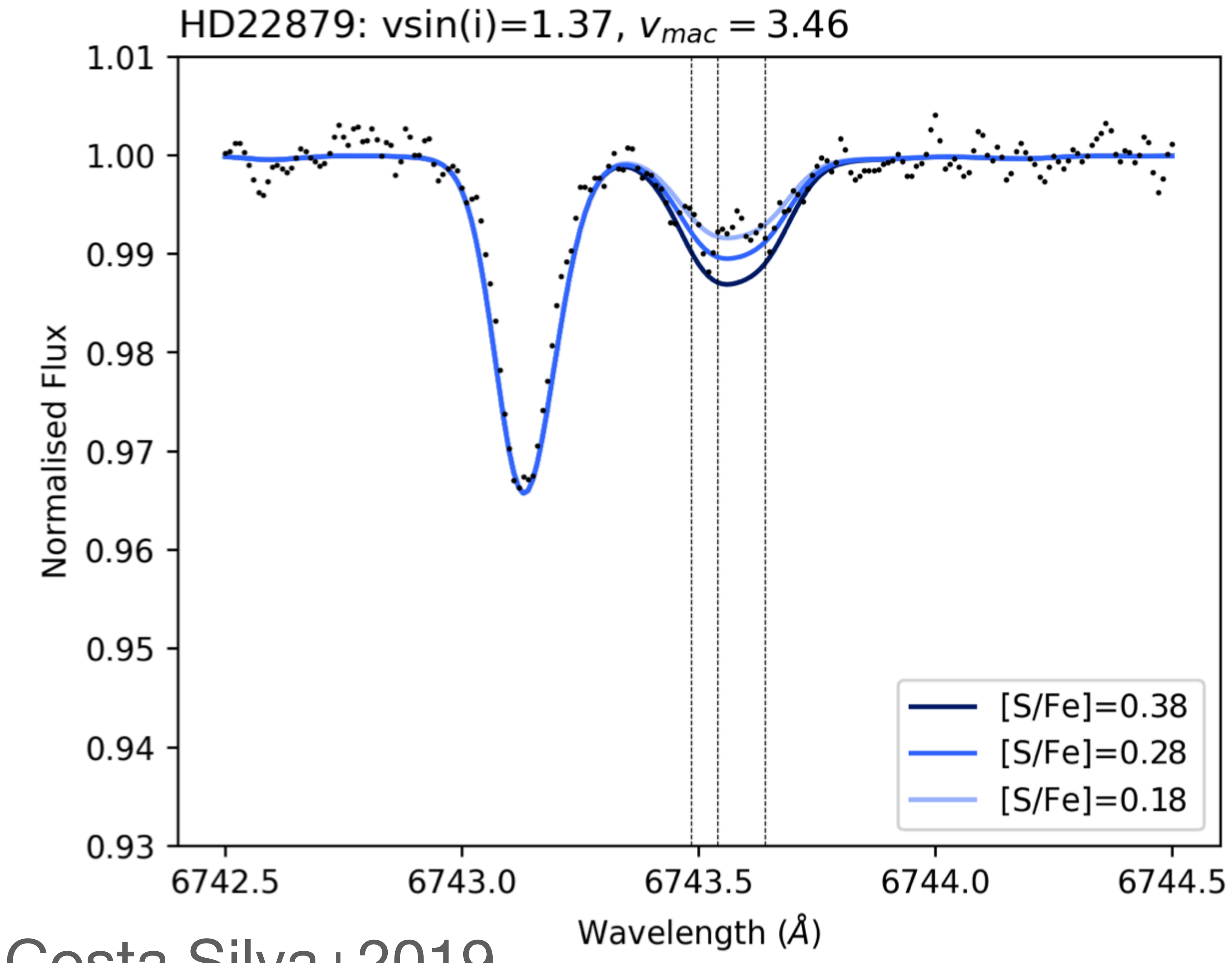
Ness+2015



Costa Silva+2019

Beyond [Fe/H] & Age

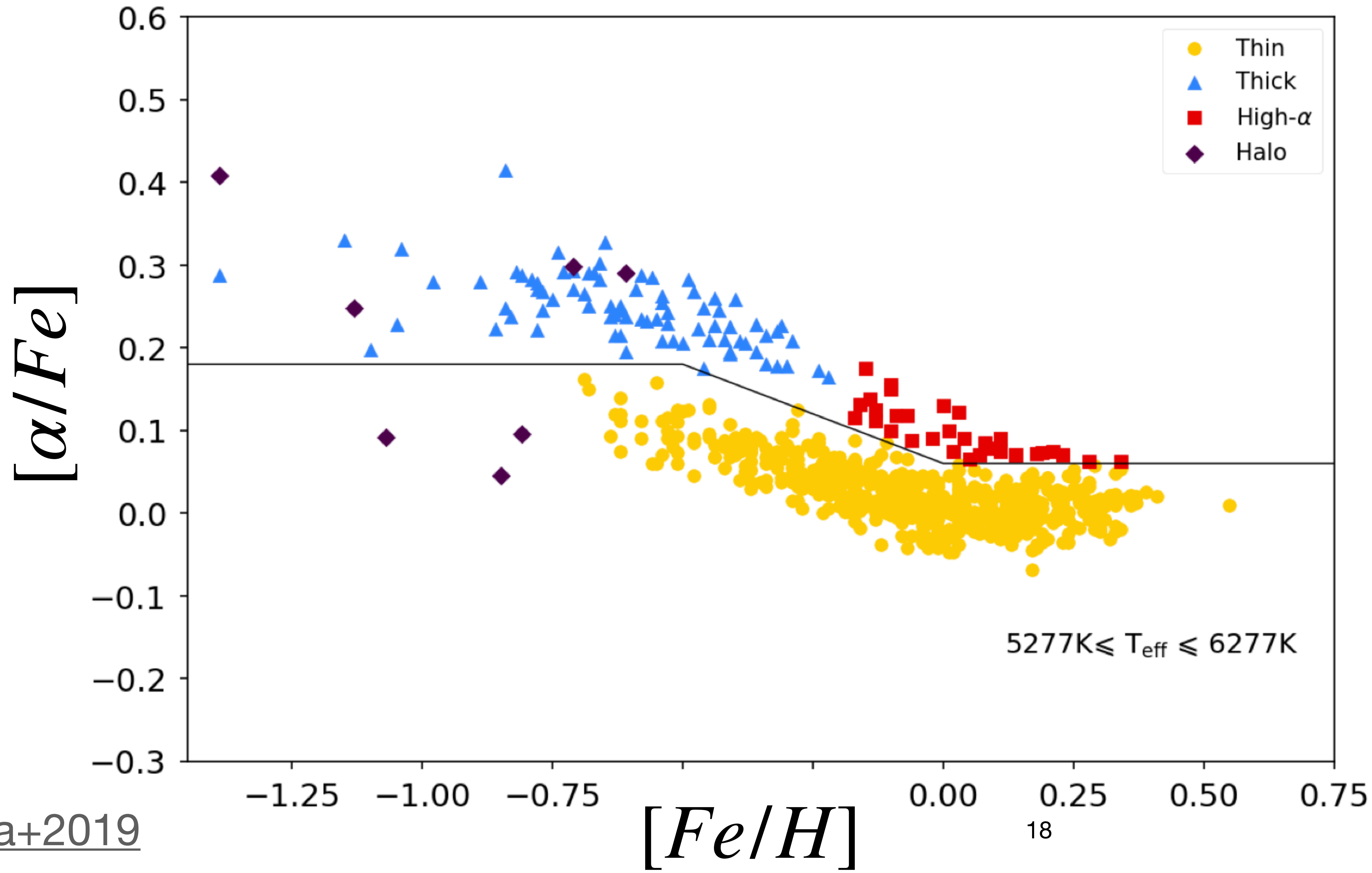
- Stars burn H -> He, mess with other elements along the way (e.g. CNO)
- AGB stars generate s-process elements in shell layers of fusion
- **SNe quickly produce r-process elements**
  - Not really the full story!

Beyond [Fe/H] & Age

- Type II SNe (massive star) produce lots of alpha elements
    - e.g. Ne, Mg. Si, S, Ar, Ca, Ti, O
- Type Ia SNe (lower mass stars, WDs) produce “iron peak” elements (and also some alpha elements)
    - e.g. Mn, Fe, Co, Ni

Alpha Elements

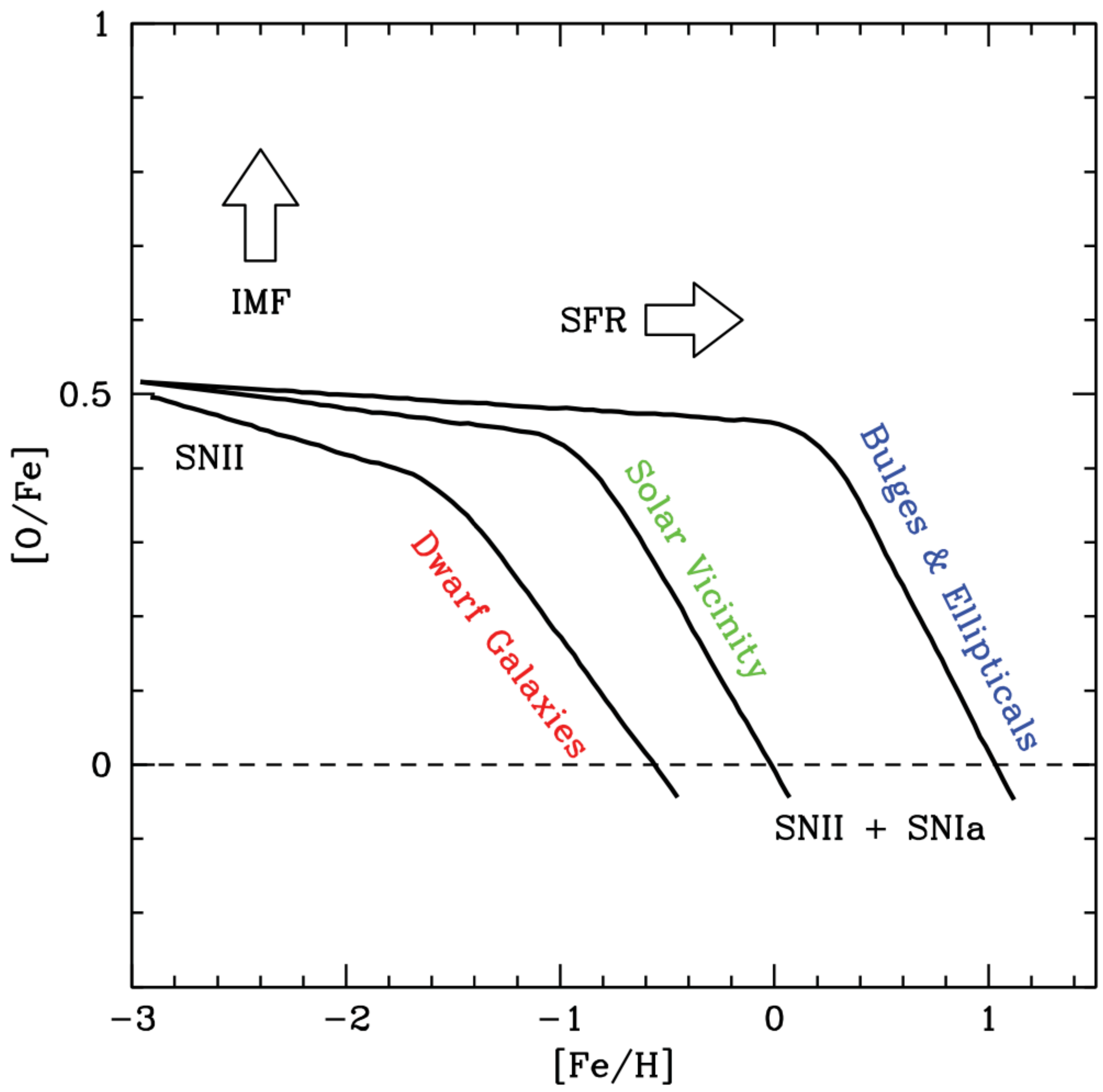
- Alpha elements / Iron Peak ≈ Massive SNe / Low-mass SNe
- Alpha elements critical for tracing evolution of galaxy!



Wallerstein–Tinsley Diagram

Costa Silva+2019

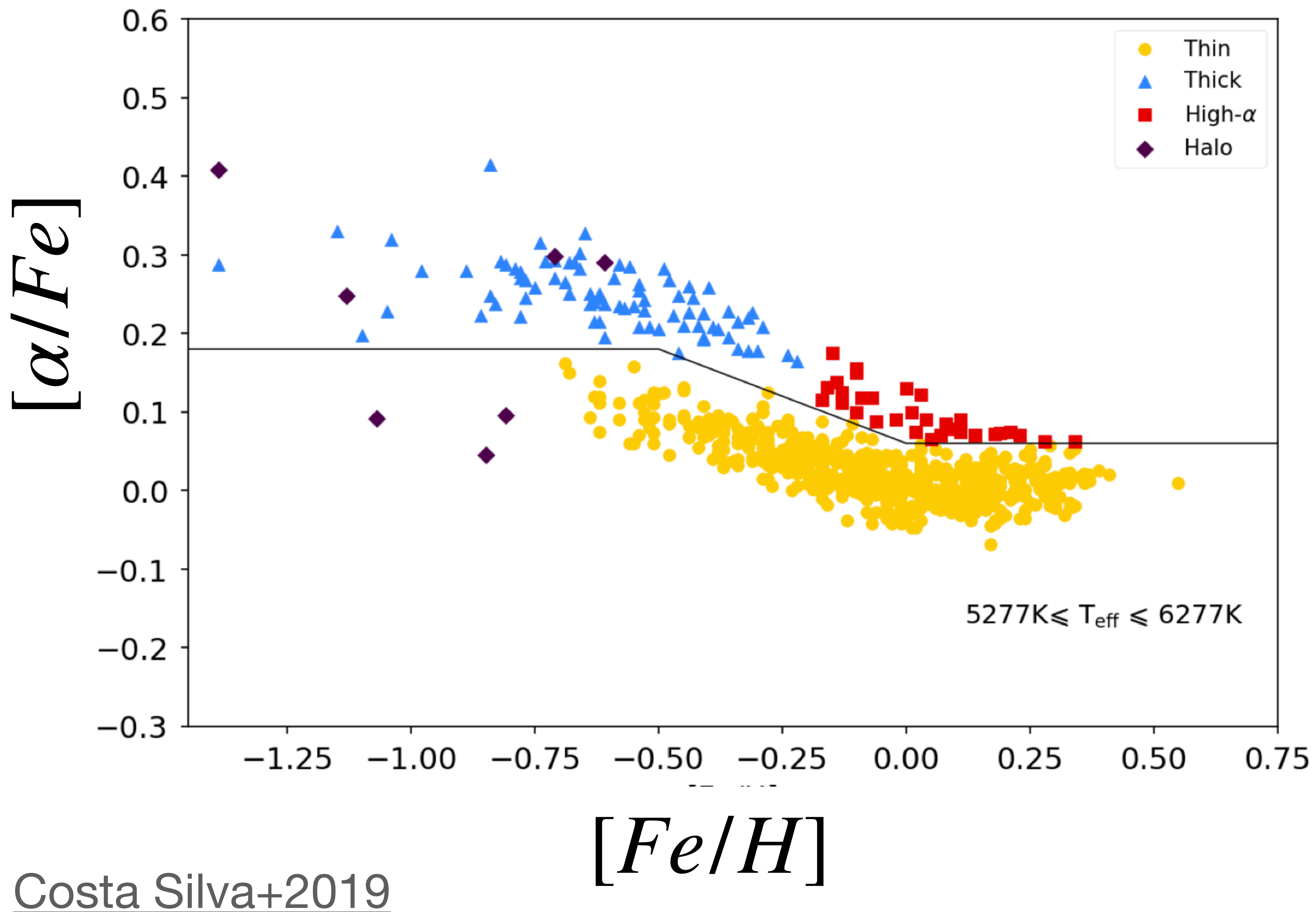
Alpha Elements



McWilliam (2016), from
Matteucci & Brocato (1990)

Alpha Elements

- **Thin & Thick disk have different star formation histories based on** $[\alpha/Fe]$



Costa Silva+2019

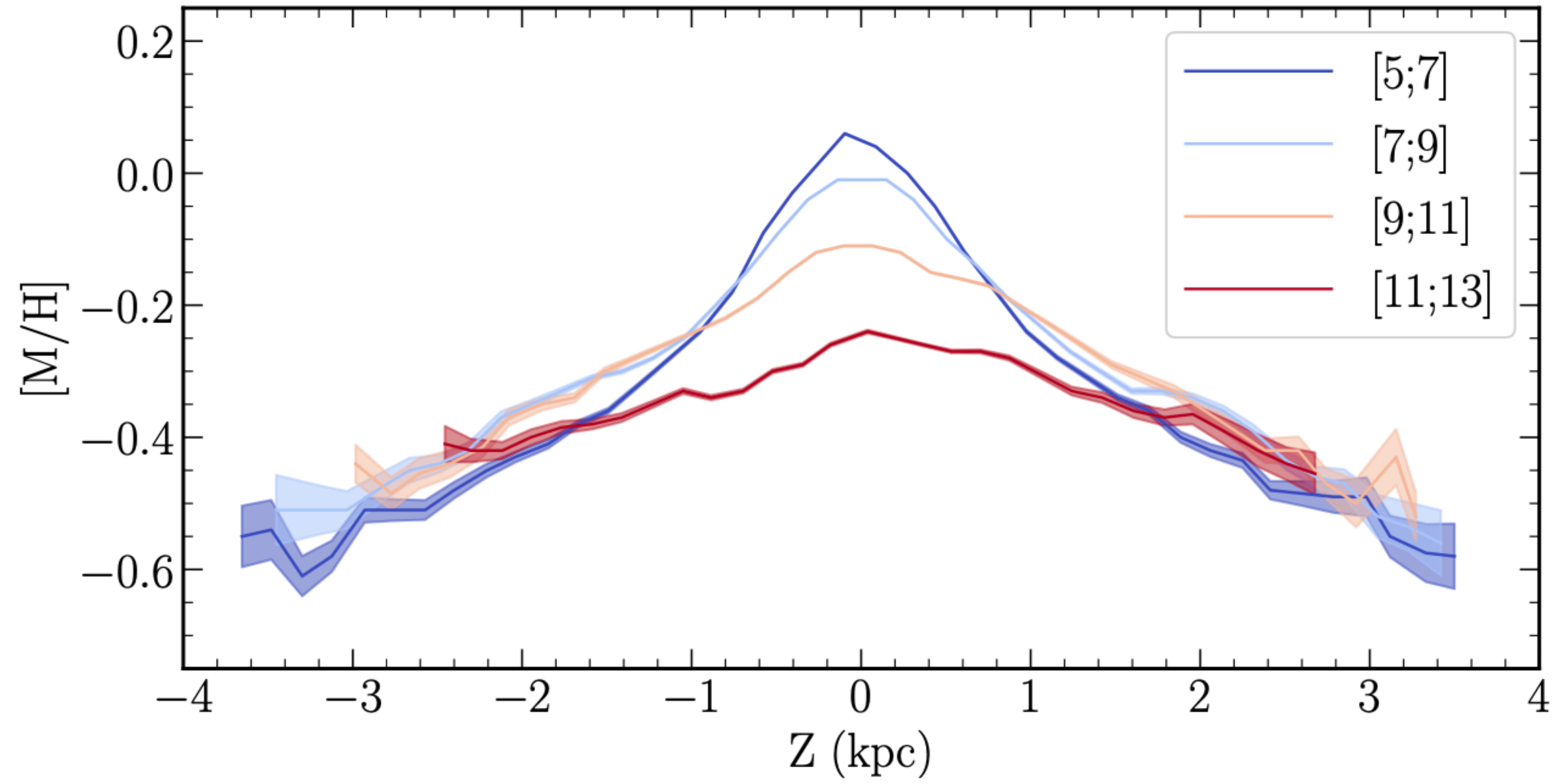
- Detailed Galactic Chemical Evolution models still tough
  - Review: Matteucci (2021) "…different chemical elements are produced on different timescales by stars of different masses."
- Lots of assumptions about enrichment timescales, "closed box" vs. in-fall, outflows, SFH…

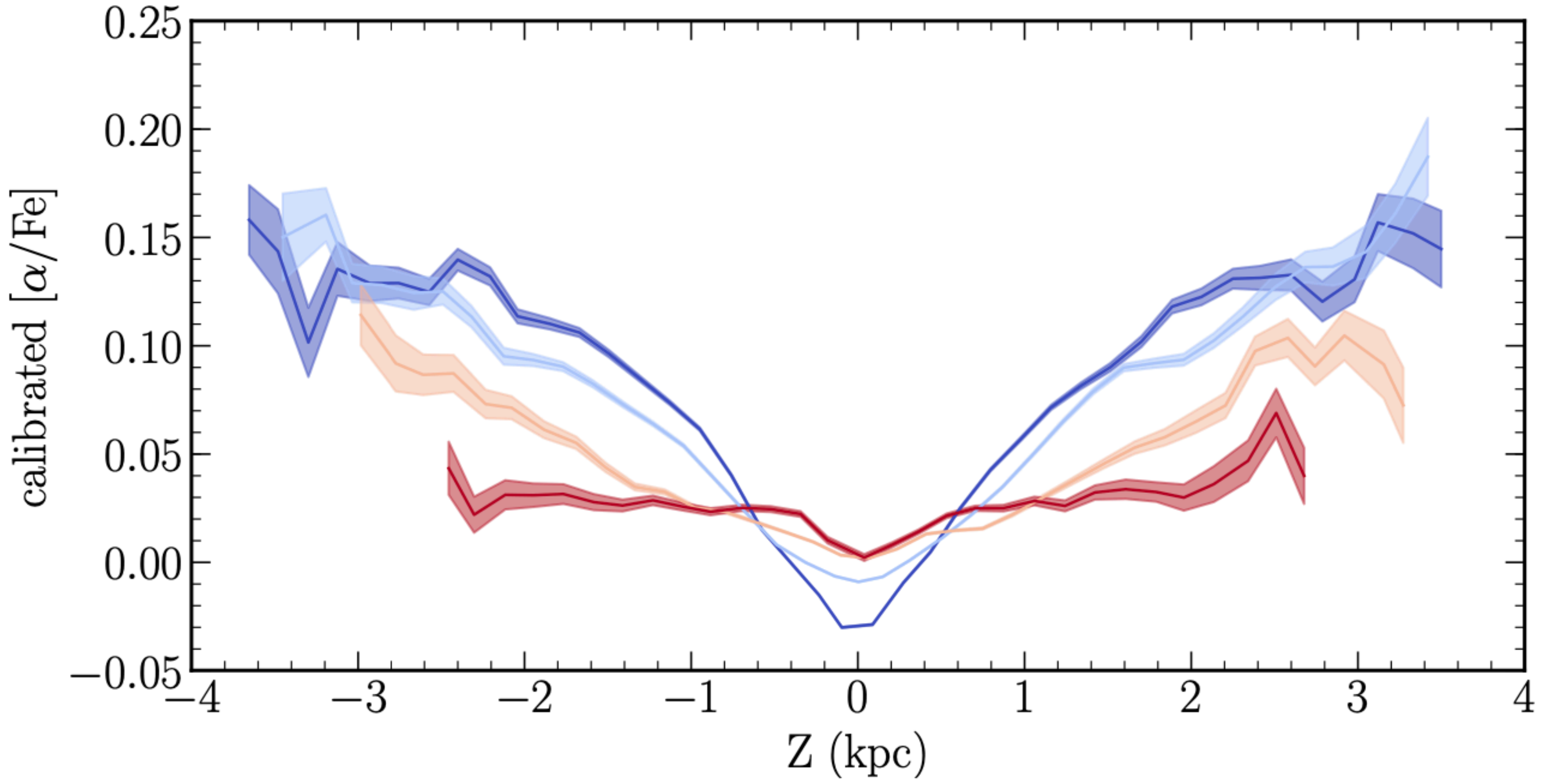
The “G Dwarf Problem”

- A classical astronomy problem: If SFH is smooth/constant, and simple picture of age -> [Fe/H]… where are the low-metallicity G dwarfs?
    - Similar “problems” found for <u>K dwarfs</u> and <u>M dwarfs</u>
- **The simple model is broken** (for the MWY): we accrete gas, outflow of gas, IMF/SFR changes, varying mixing/recycling rates

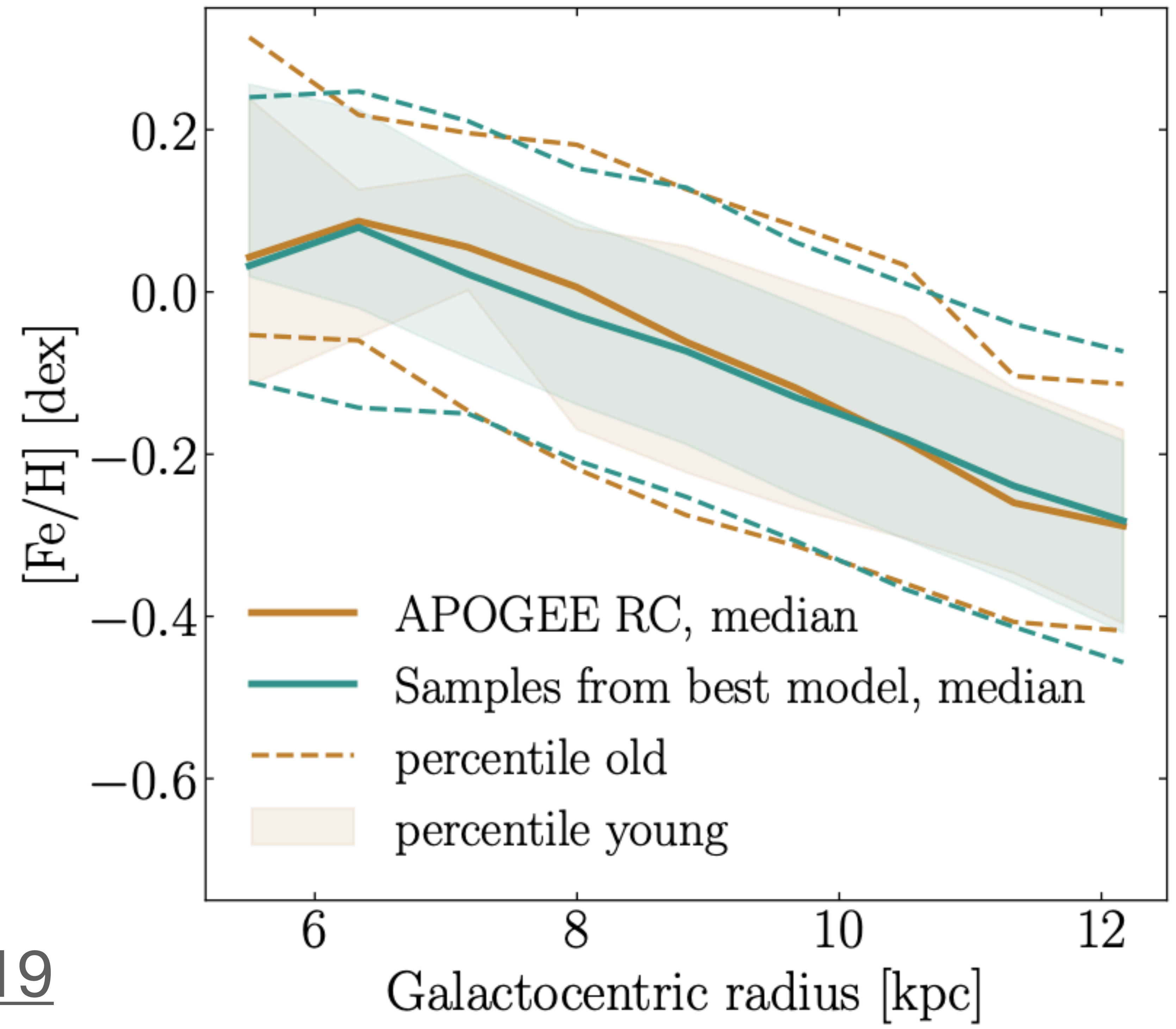
Inside-Out Growth of MWY Disk

- Metallicity lower in outer disk.
- Star formation more active in inner disk!



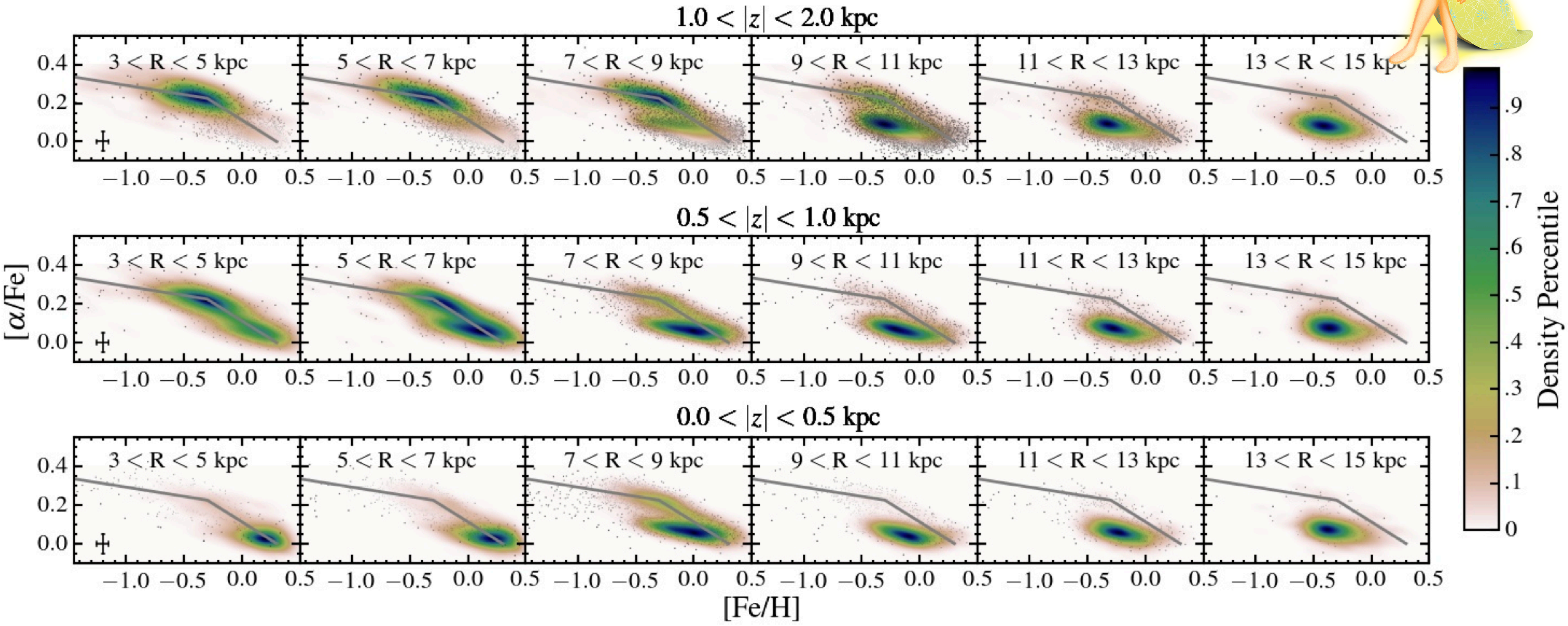


Gaia+2022



Frankel+2019

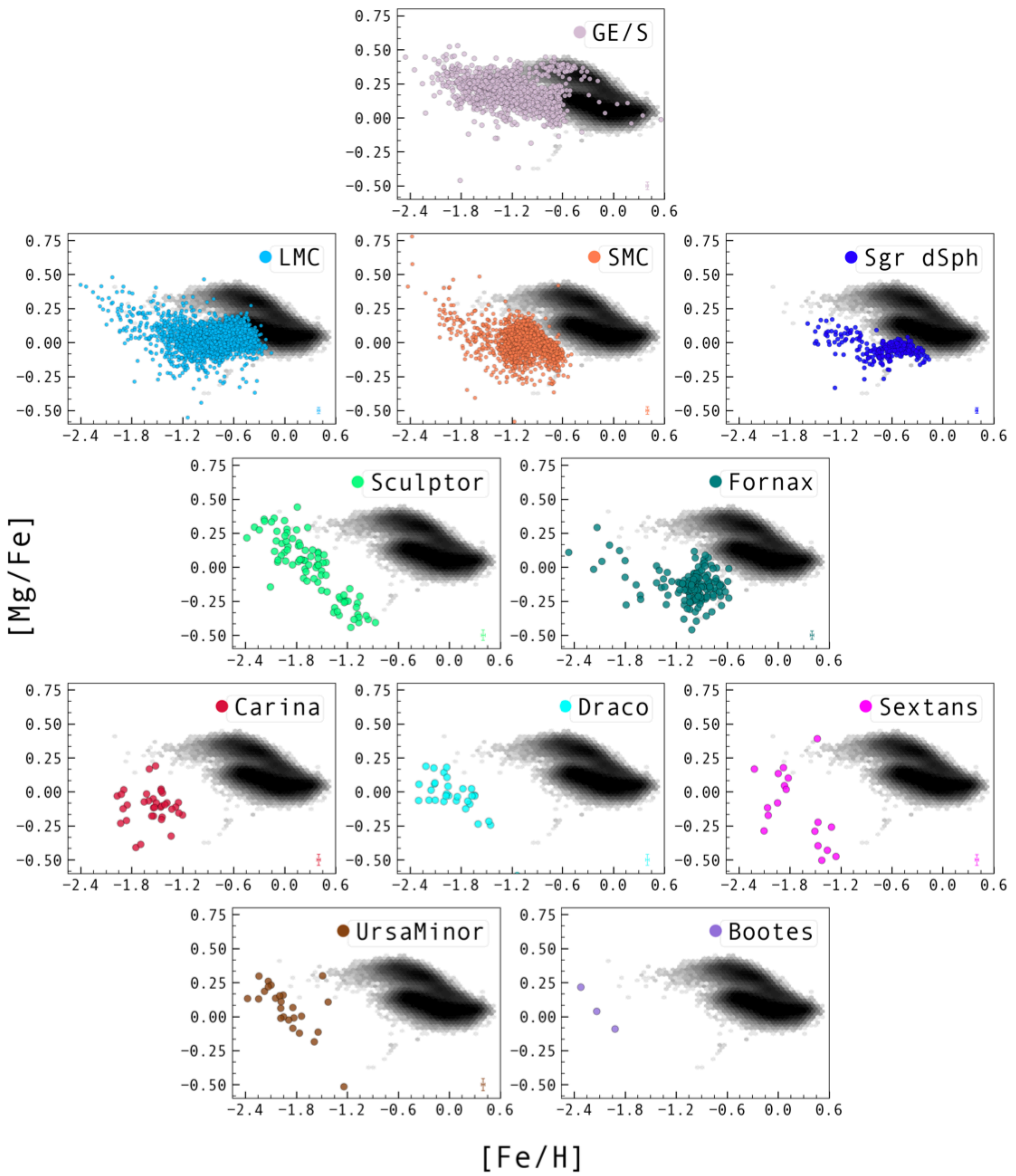
Inside-Out Growth of MWY Disk



Hayden+2015

Accretion History

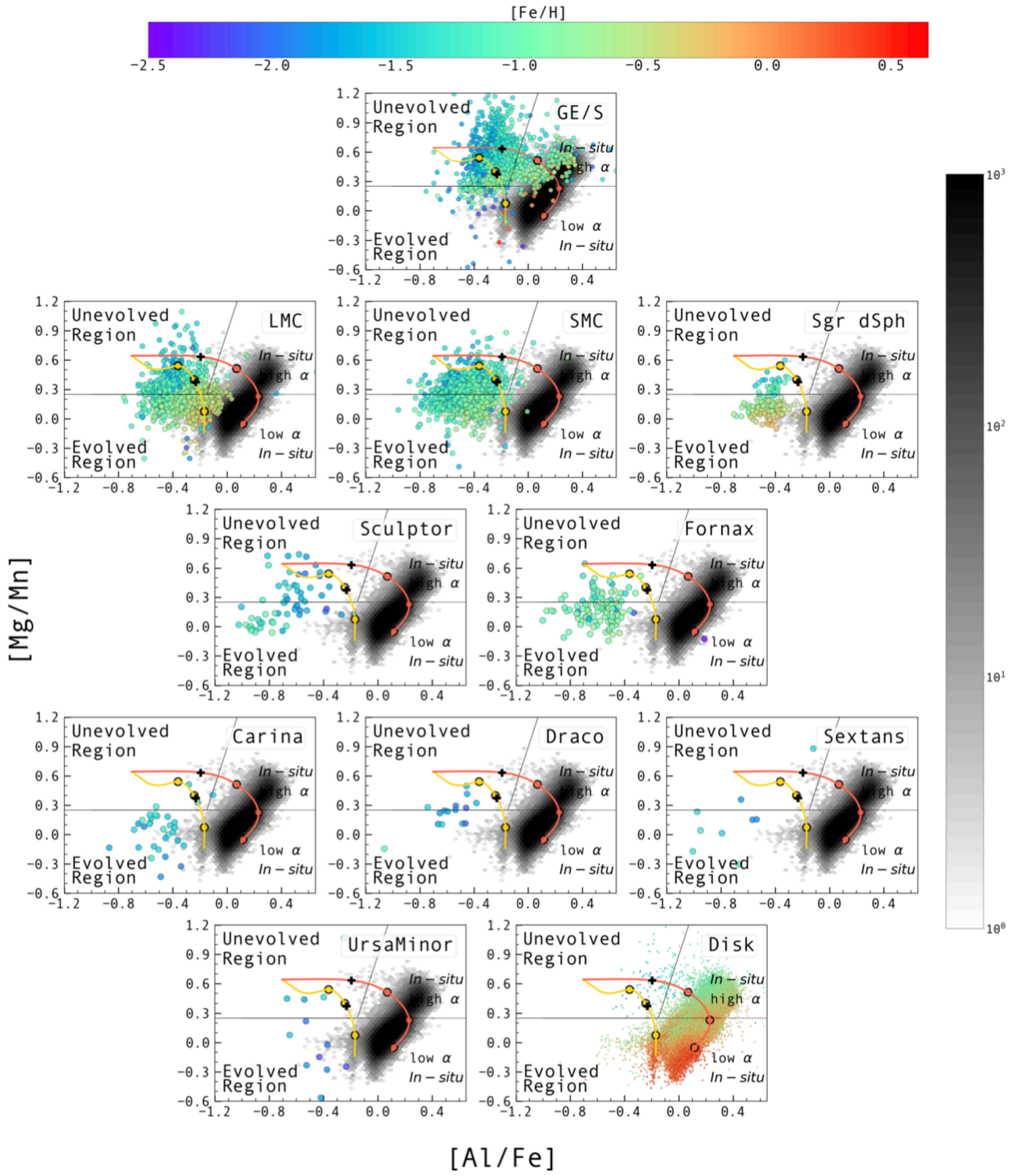
- These accreted satellites (were: dwarf galaxies, now: tidal debris) have distinct chemistry from MWY
  - Also from SMC/LMC



Fernandes+2023

Accretion History

- Can be used to find NEW substructure (how much thick disk & halo come from distinct mergers?)
- Can help estimate mass of the merger
- Constraints on dSph formation, feedback, big simulations…

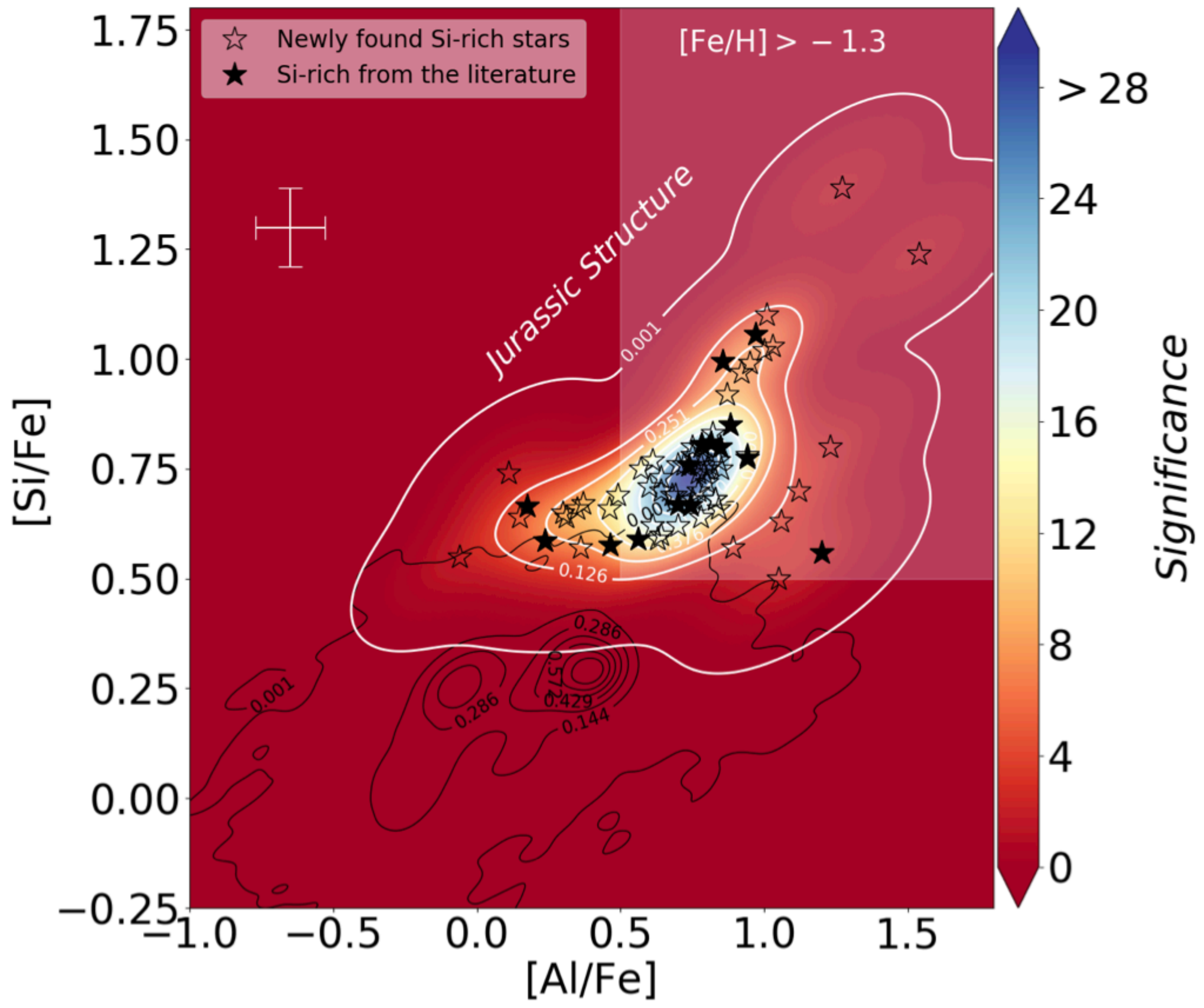


Fernandes+2023

Finding New Remnants/Structures

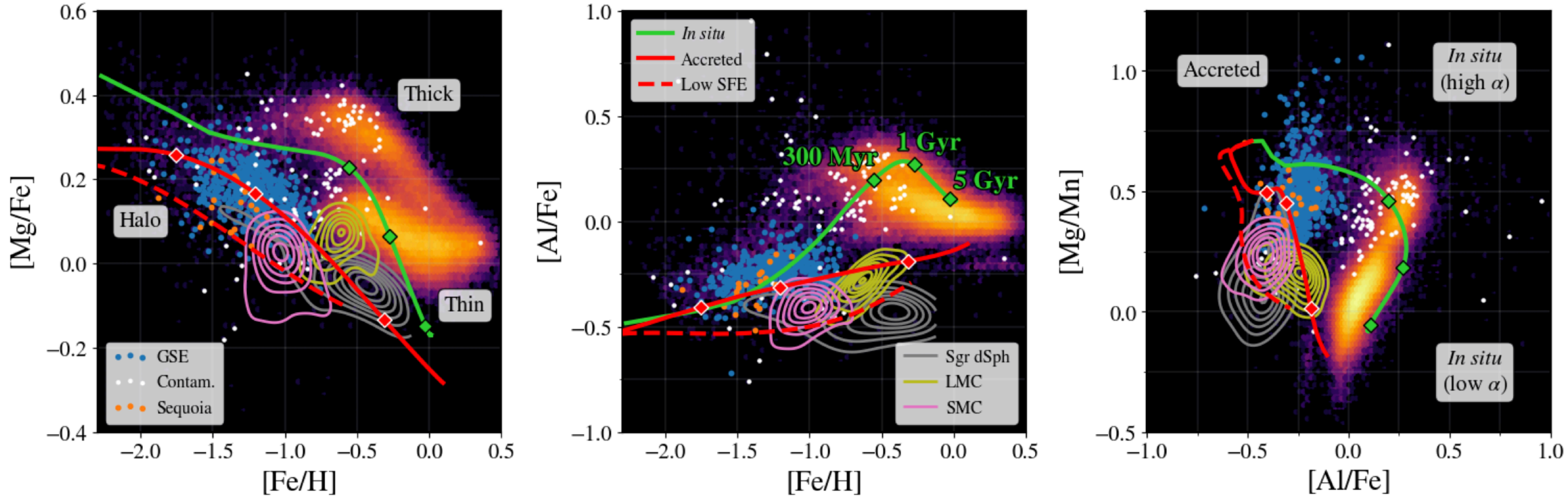
- GE/S is the big news, of course
- Many other distinct, smaller populations cropping up… with great names!
    - e.g. Sequoia, Thamnos, Jurassic, Cetus, I'itoi, Pontus

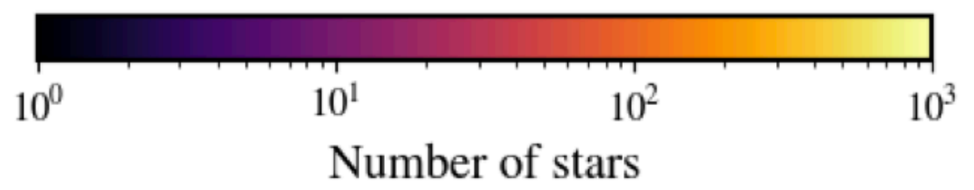
🚨 Most of these discoveries 🚨
published in last ~2yrs!



Jurassic

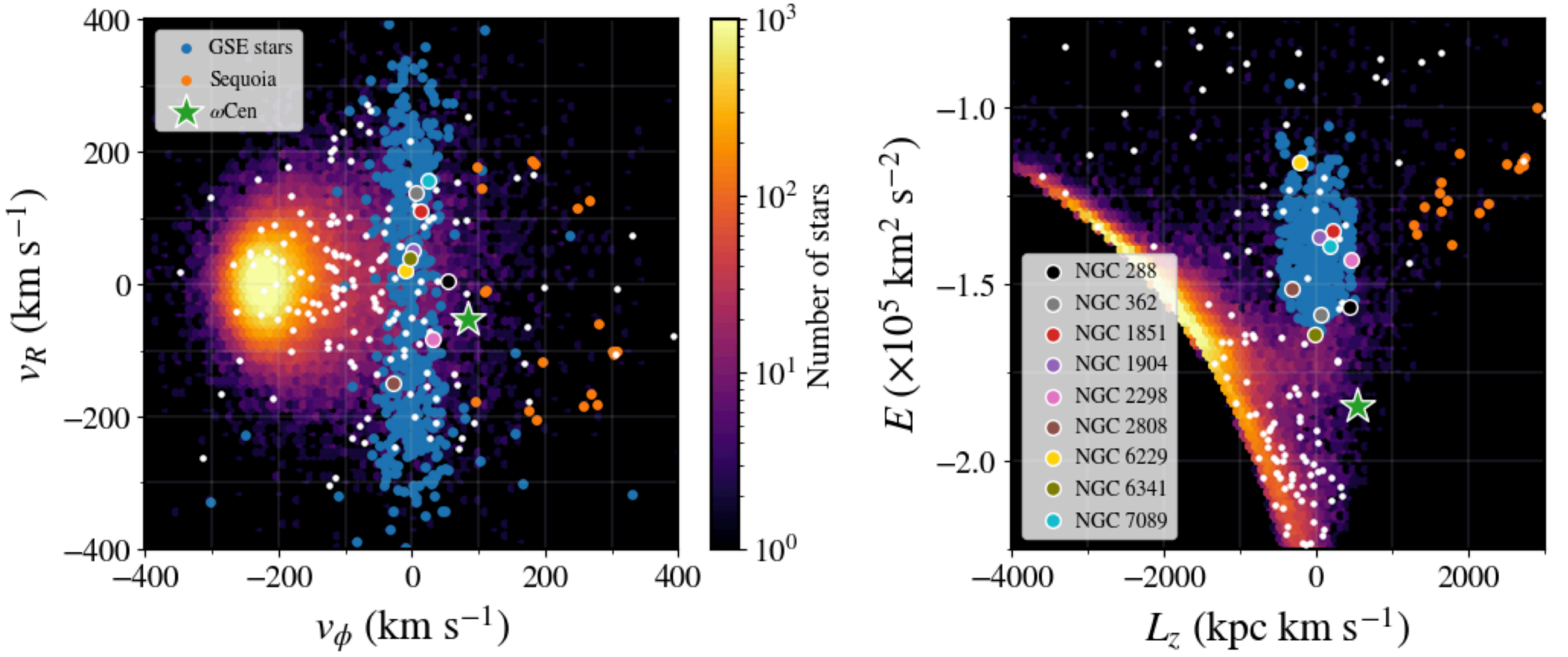
Finding New Remnants/Structures





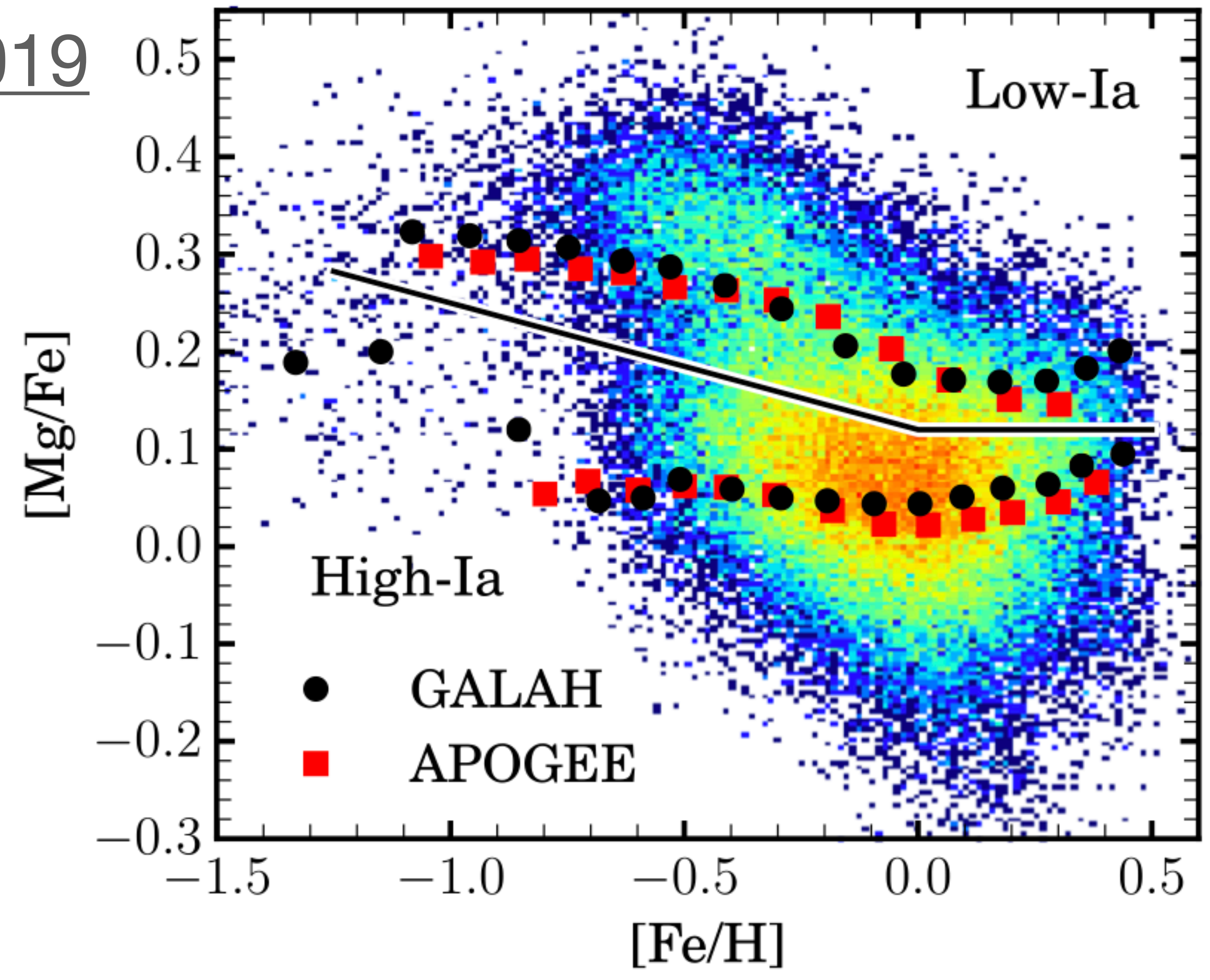
Limberg+2022

- Combo of kinematics & chemistry is powerful!



The Future

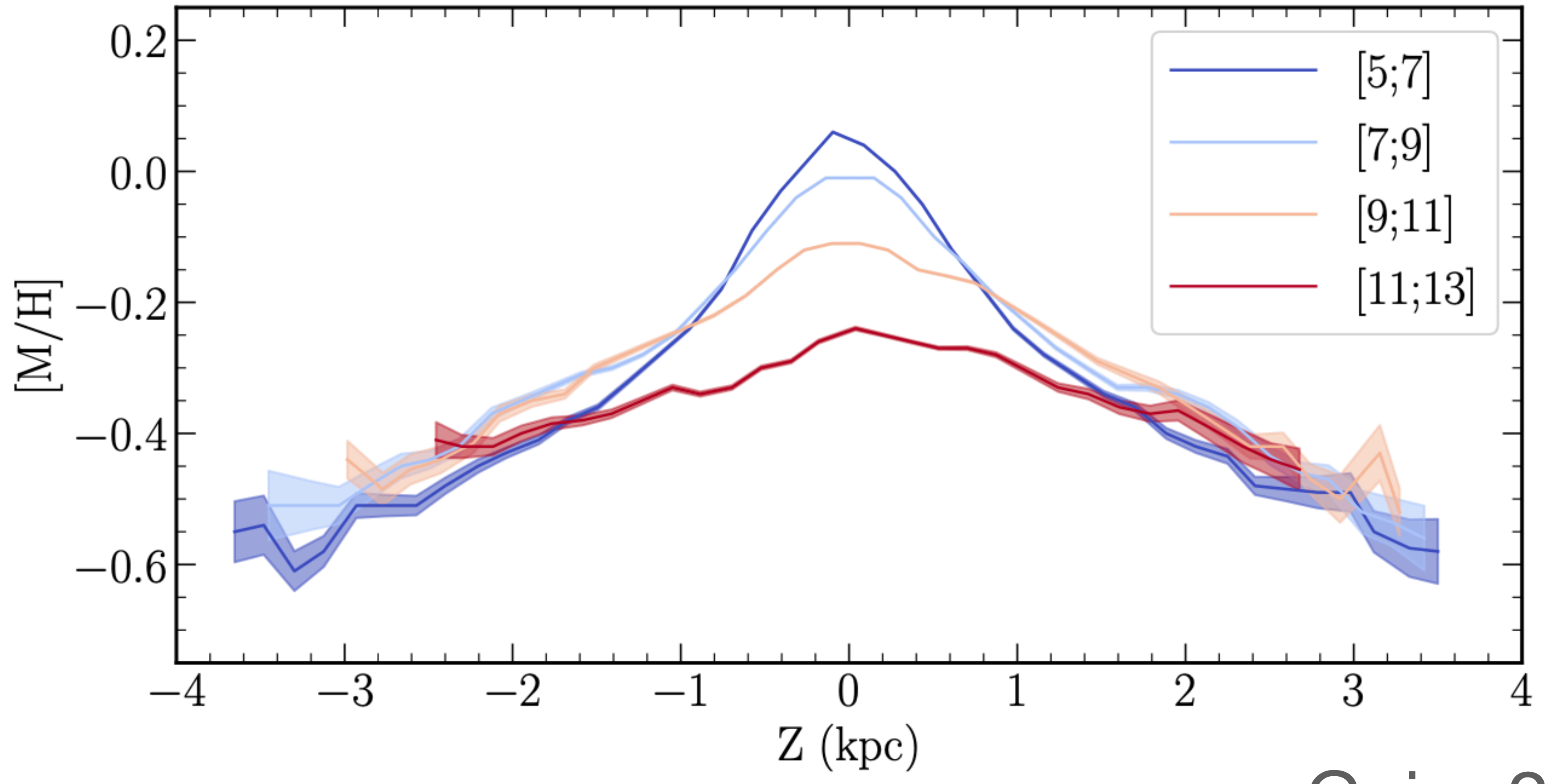
Griffith+2019



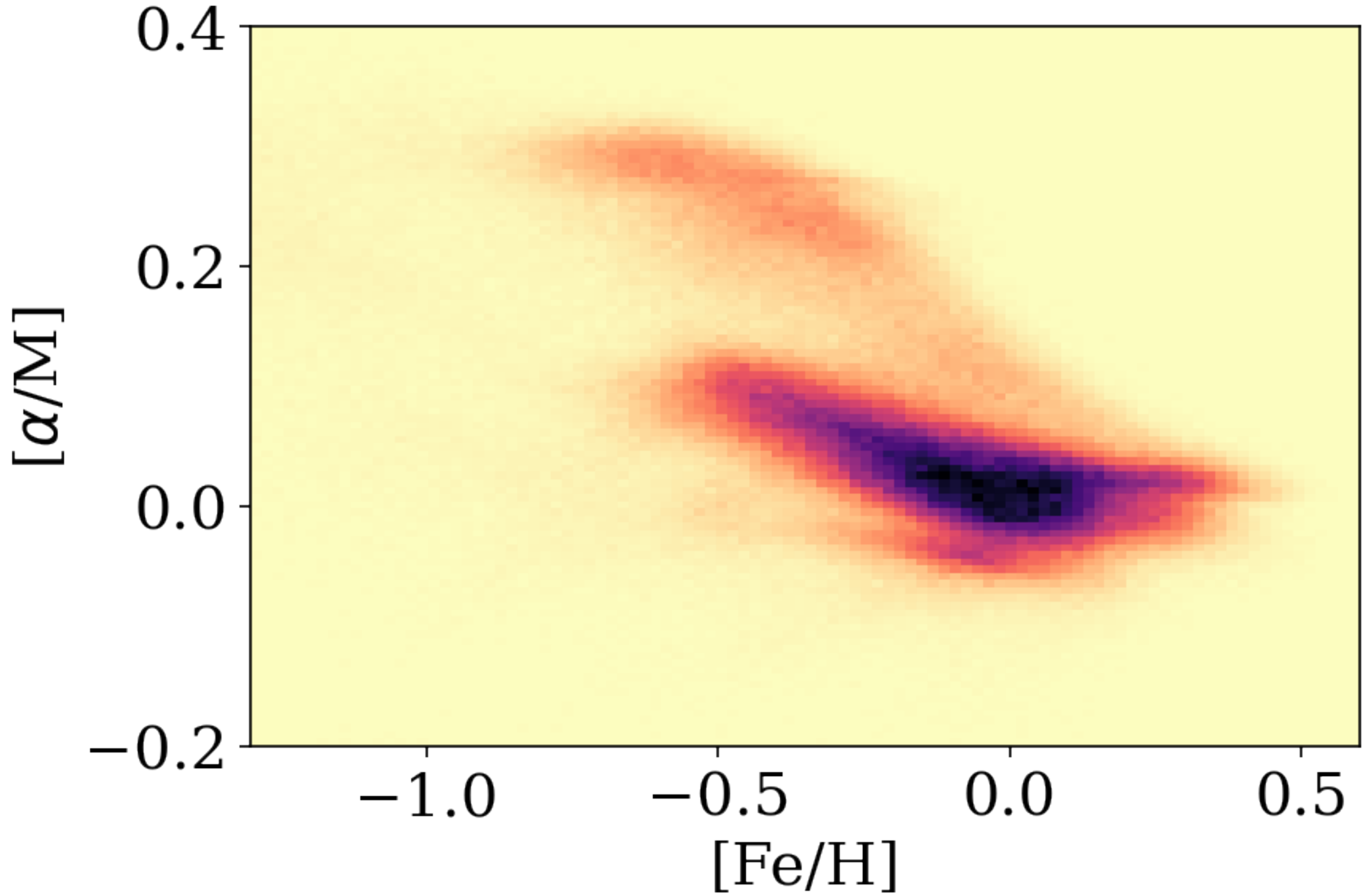
- Finding more kinematic & chemical sub-structure will be productive for a while, more surveys contributing!
    - Probably some fun ML/algorithms stuff here
    - Starting to see time-domain (e.g. asteroseismology) play a part too
- Improved galactic chemical evolution models,
    - Model star formation within disk(s)/halo/bulge + *many* specific mergers
    - Detailing specific element ratios beyond simply Fe, α, etc
    - Improved enrichment and mixing timescales (globular cluster mult. pops?)

Homework 3

- **Look at the Wallerstein – Tinsley diagram from APOGEE**
- Thin/thick disk are easily visible
  - A *bunch* of sub-populations too!
- Disk structure!



Gaia+2022



🚨 Most of these discoveries 🚨 published in last ~2yrs!

Next Time

- Star Formation History
  - How do we measure stellar ages??