An overview of current large-scale stellar spectroscopic surveys

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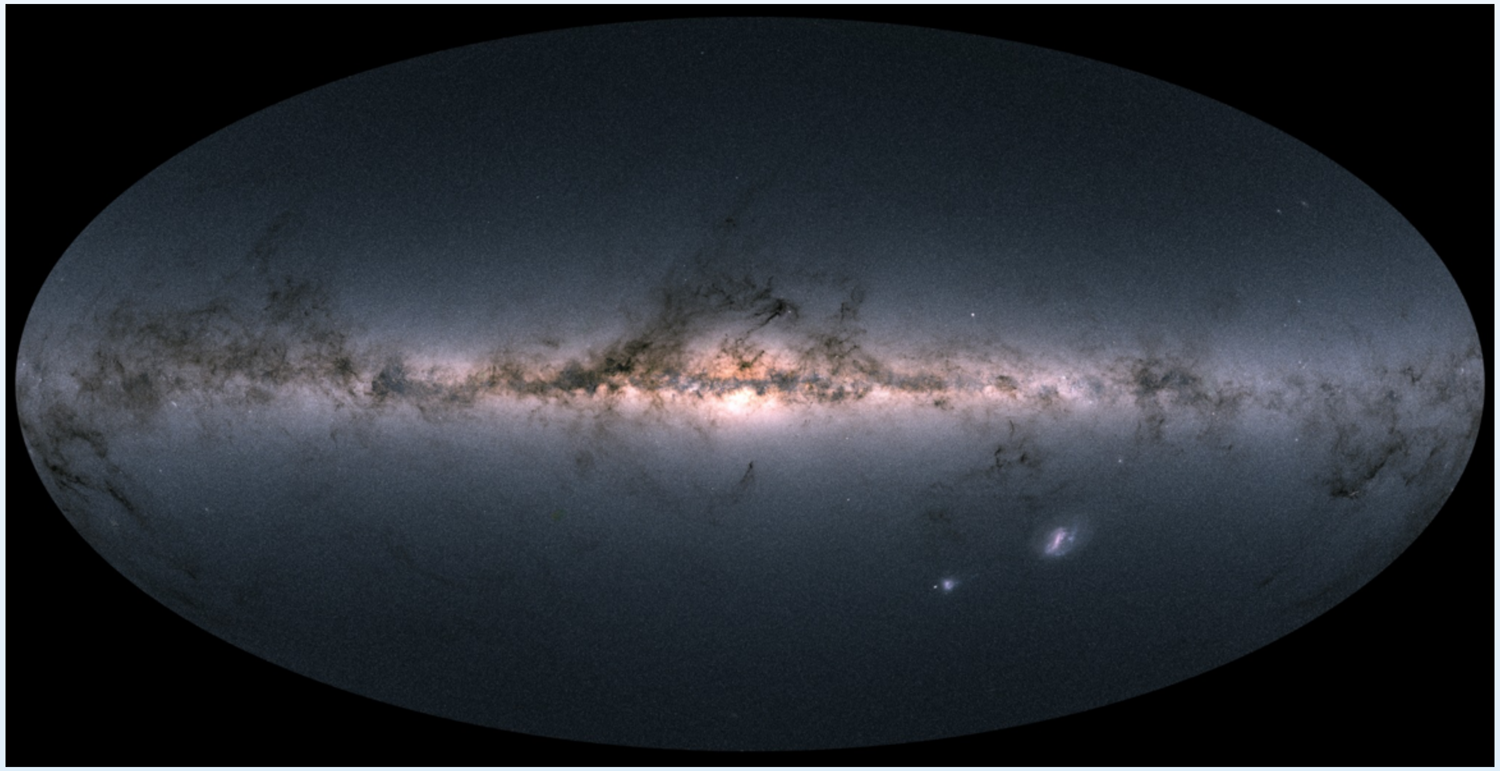
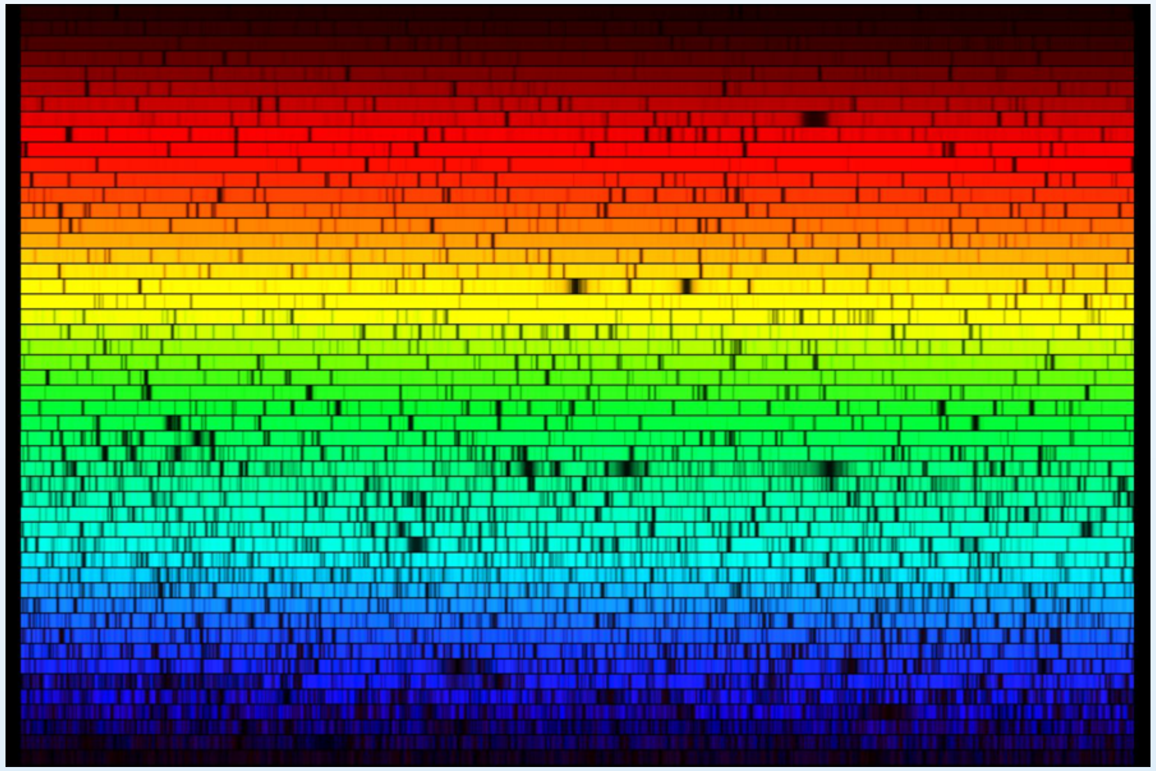




Some questions before we start

(Q1) What is your experience so far with large spectroscopic surveys?

(A) I am/was involved in research using a large spectroscopic survey

(B) I want to know what large spectroscopic surveys can to for my research

(C) I have never used data from a large spectroscopic survey for my research

(Q2) How do you stay up to date with the on-going research in your field?

(A) I read arXiv's astro-ph

(B) I read the reviews of my field

(C) We have regular group meetings with presentations of recent papers

(D) None of the above

(Q3) How often do you read astro-ph?

(A) Every morning on my way to work

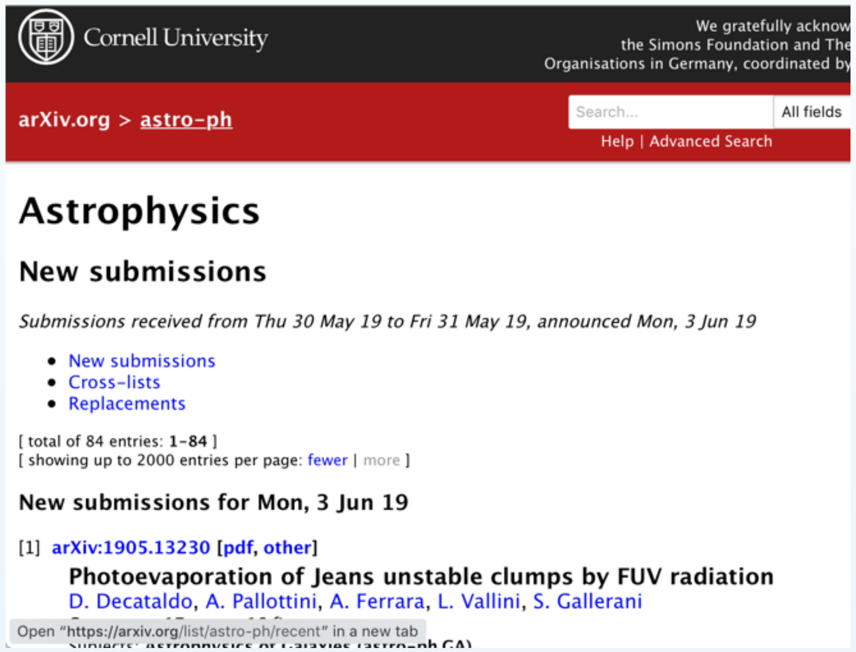
(B) About once a week when I remember

(C) Never

(D) It varies wildly

Some questions before we start

https://arxiv.org/list/astro-ph/new https://voxcharta.org https://arxiver.moonhats.com



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(C) Never

(D) It varies wildly

Sven Buder (MPIA)

Some great advice I got during my PhD

(1) Choose your PhD project wisely, (2) choose your PhD supervisor wisely, (3) Write, write, write, (4) automate everything, (5) learn project and time management, (6) never underestimate your audience willingness to hear something they already know, (7) know your target audience, (8) ensure that senior scientists know your work, (9) keep a healthy work-life balance, and (10) enjoy it!

Martin Asplund

Try to break the research into small publishable units

Melissa Ness

What's the Δscience?

Tim Beers

What's the bigger picture?

Hans-Walter Rix

The bigger picture of this lecture

What are the questions we want to answer?

Which properties do we have to measure for that?

How can we do that (with spectroscopic surveys)?

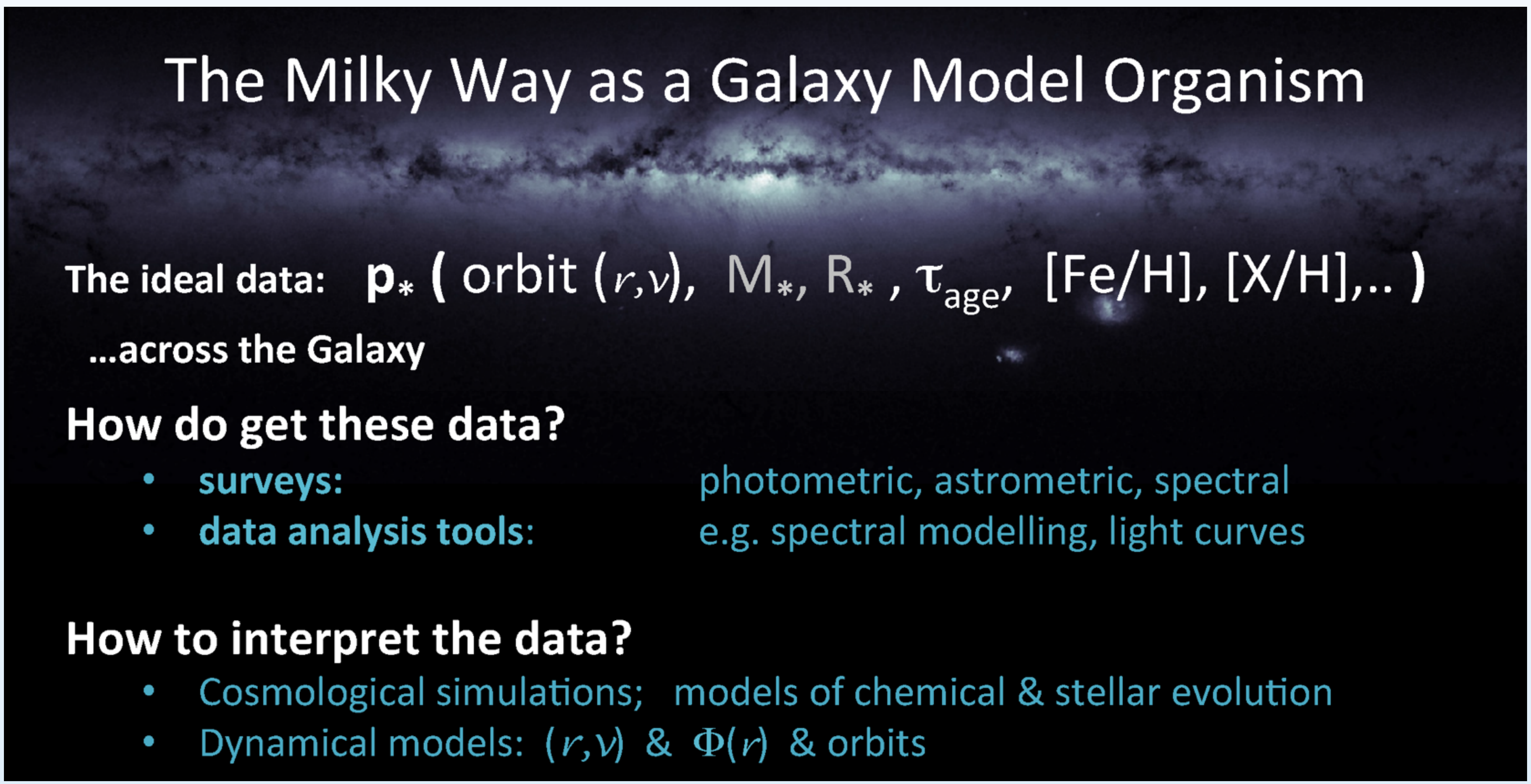
What is the industrial revolution of Galactic Archaeology?

3 surveys in more detail

Open questions and issues (your future research?)

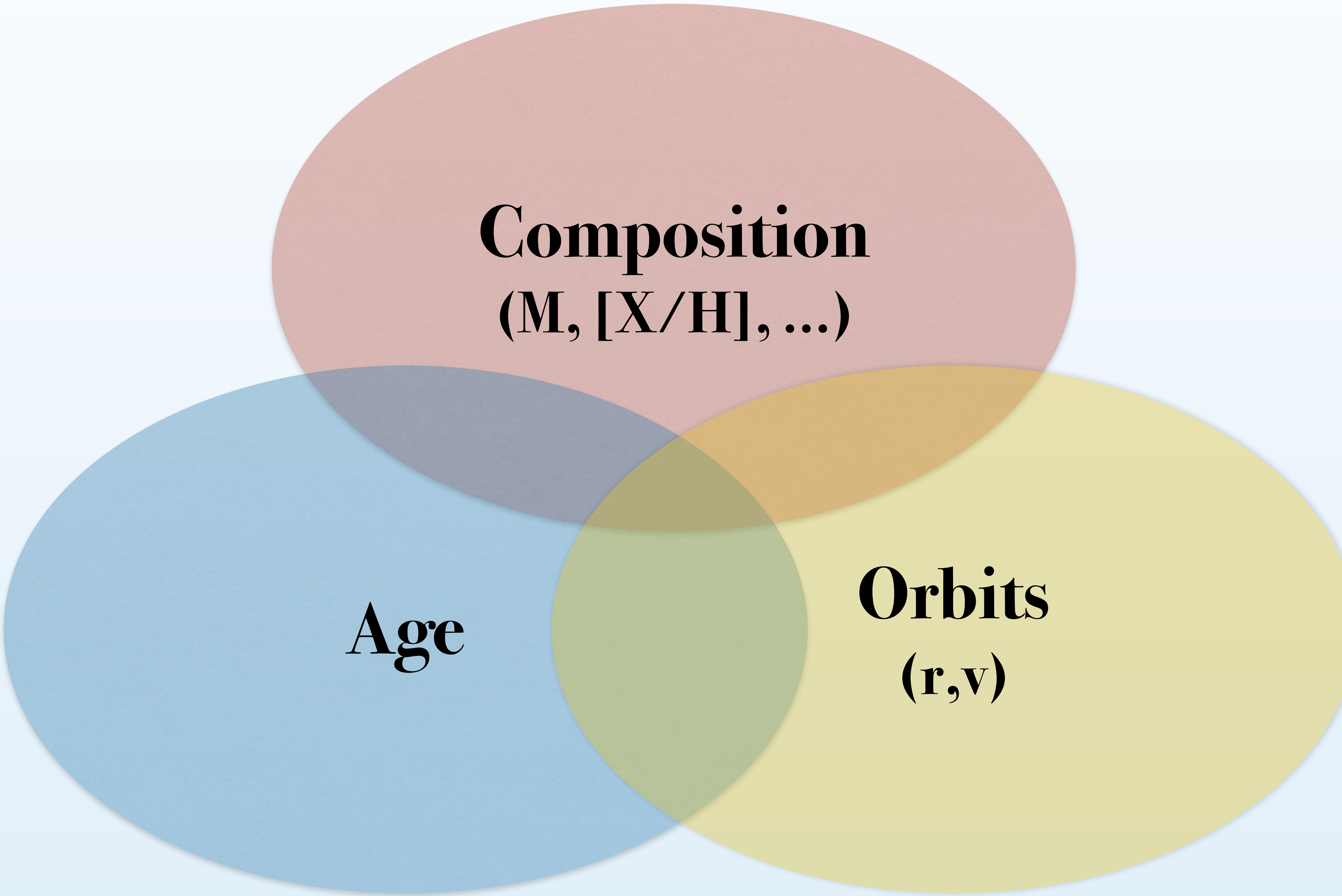
What do we want to know about the MW?

- What processes set the Milky Way's present state/structure?
- How much information memory does a galaxy retain?
- How does a galaxy self-pollute (and what types of stars did it)?



Credit: Rix, see also Rix & Bovy (2013)
http://adsabs.harvard.edu/abs/2013A%26ARv..21...61R

What do we want to know about the MW?



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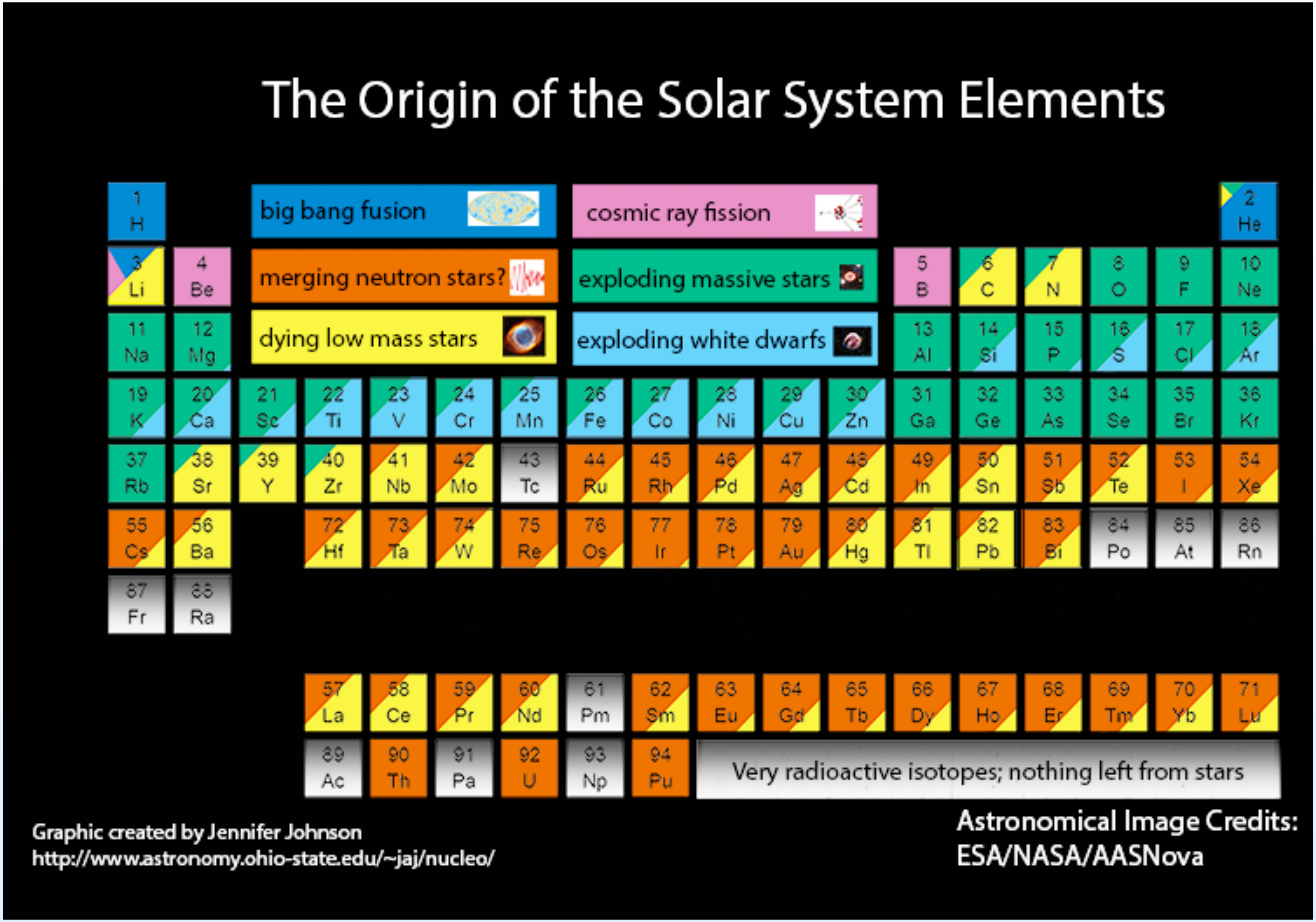
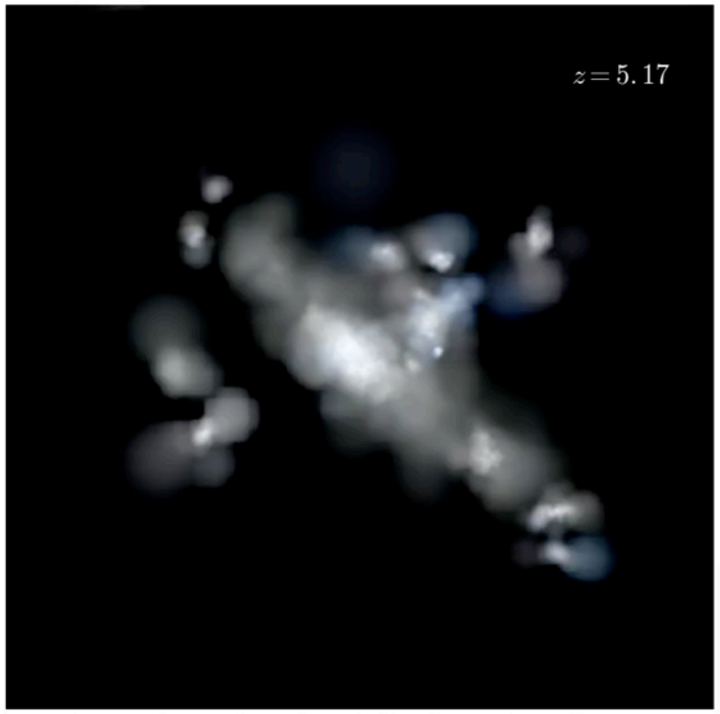
Chemical "self-pollution"



Chemical compositions to reconstruct enrichment history

Early turbulent formation → settles into Galactic disk (75% of stellar mass)

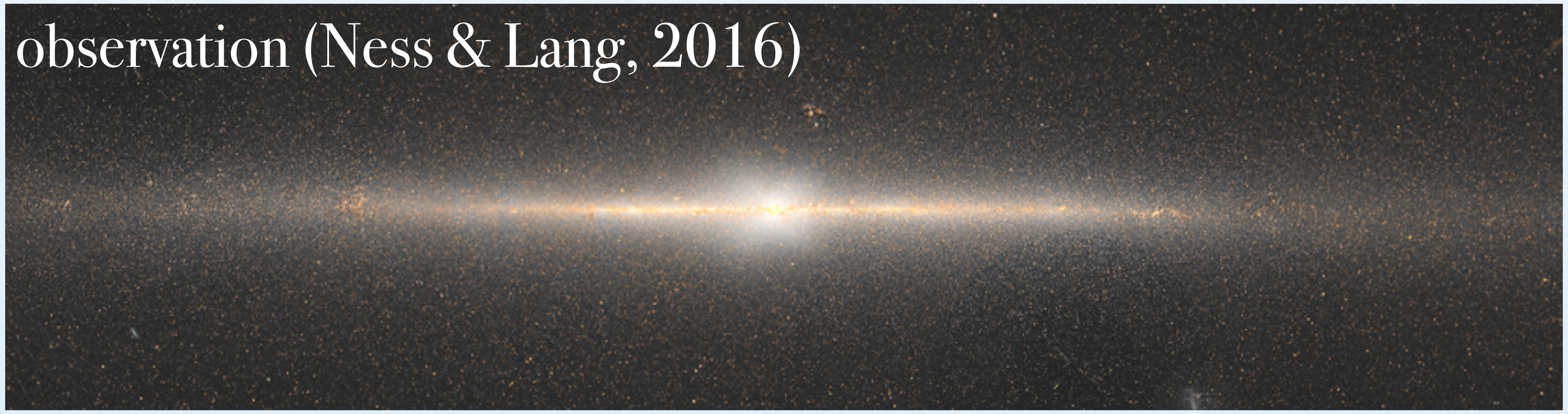
Animation by T. Buck (MPIA, NYUAD) based on NIHAO simulations



Animation by T. Buck (MPIA, NYUAD) based on NIHAO simulations

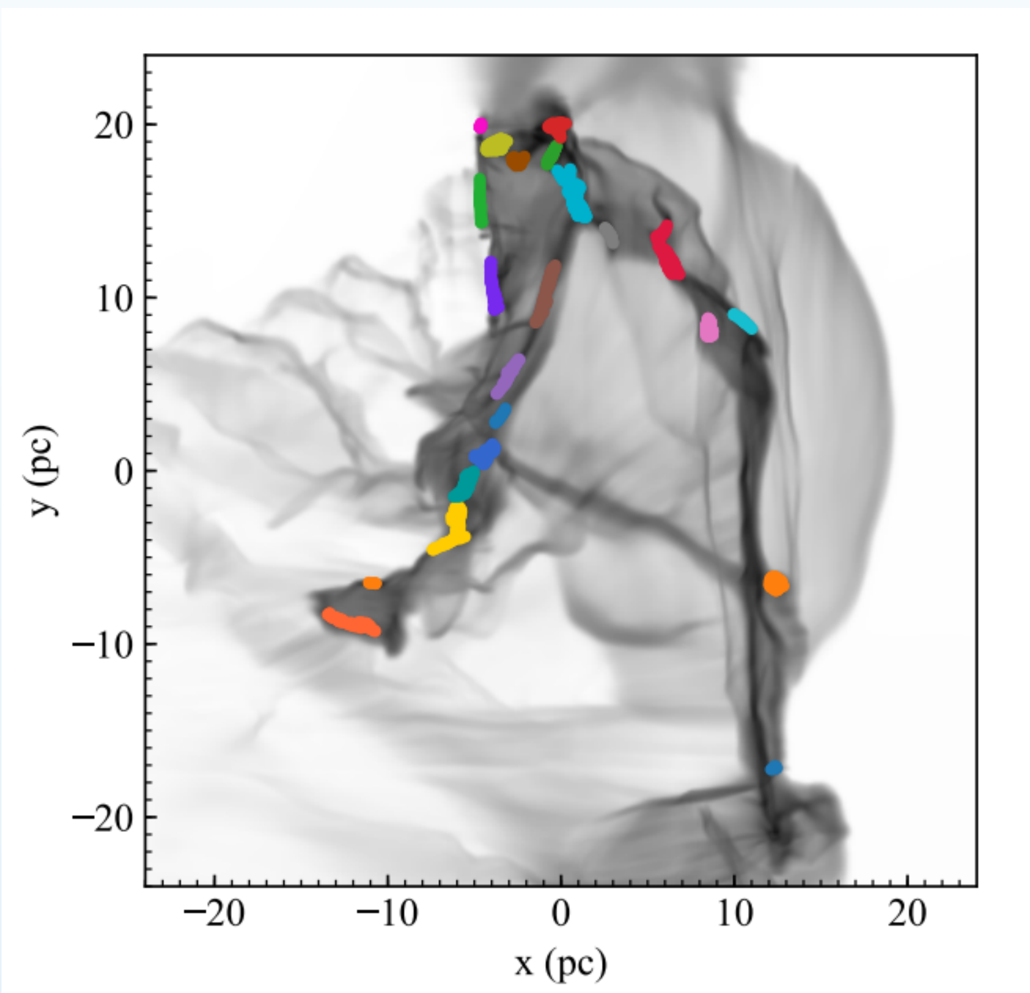
Buck et al., 2019
http://adsabs.harvard.edu/abs/2019ApJ...874...67B

positions and dynamics change, chemical compositions birth properties



Chemical tagging

- Stars form in clusters, with presumably identical abundances



Armillotta et al. (2018)
http://adsabs.harvard.edu/abs/2018MNRAS.481.5000A

these disperse in forming the disk

- One prospect to trace back disk assembly – **chemical tagging**
- Identify individual stars across the disk from the same birth sites using **large vector of chemical abundances**

Bland-Hawthorn & Freeman (2010)
http://adsabs.harvard.edu/abs/2010ApJ...713..166B

Under the umbrella of Galactic Archaeology

With the bigger picture in mind,
surveys address specific key science questions:

Survey A: Up to 30 different abundances for
1,000,000 stars within a few kpc of the Sun

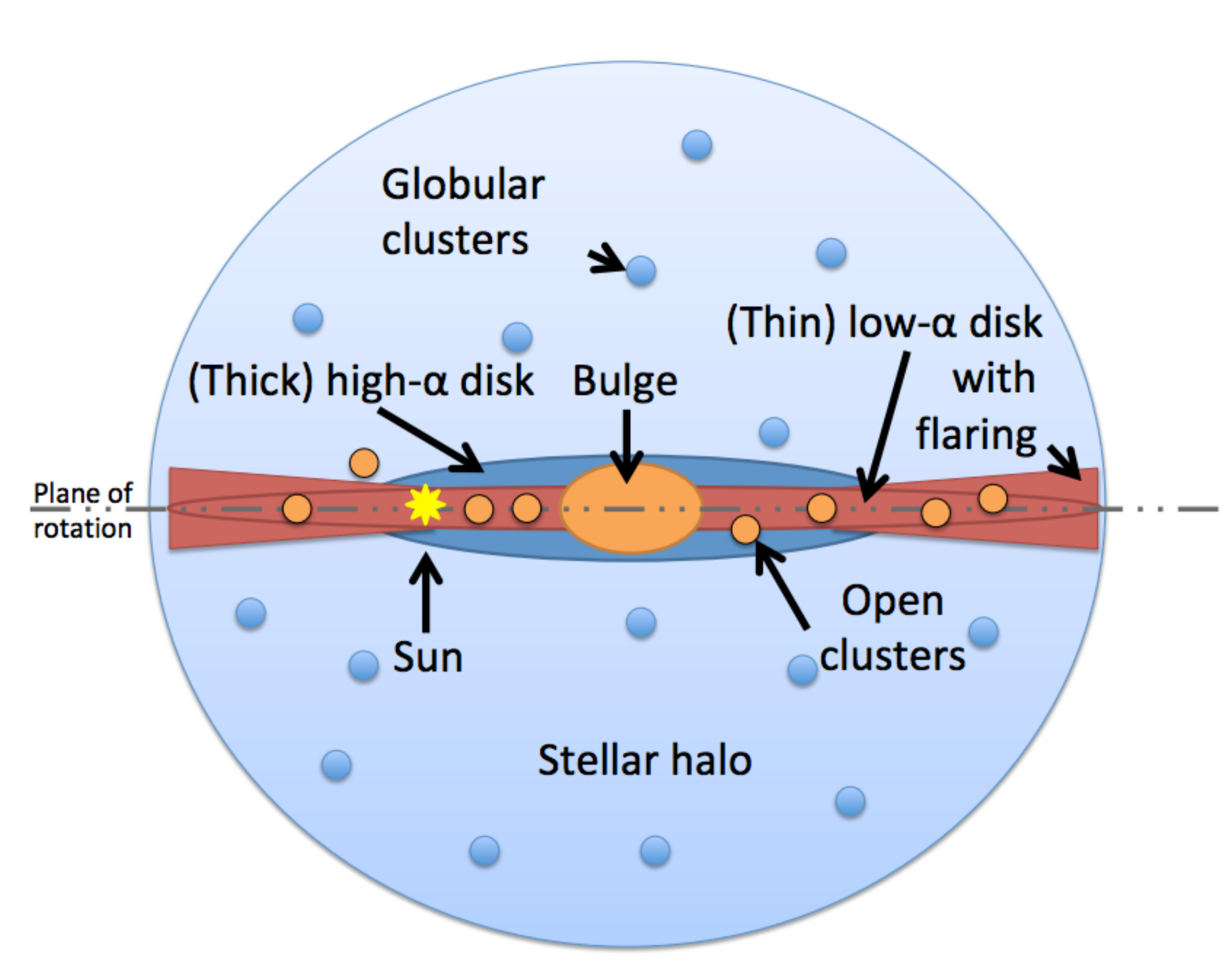
-> Chemical tagging and
discriminative information in abundances

Survey B: 15 abundances for 300,000 stars
across 20 kpc of the Galaxy

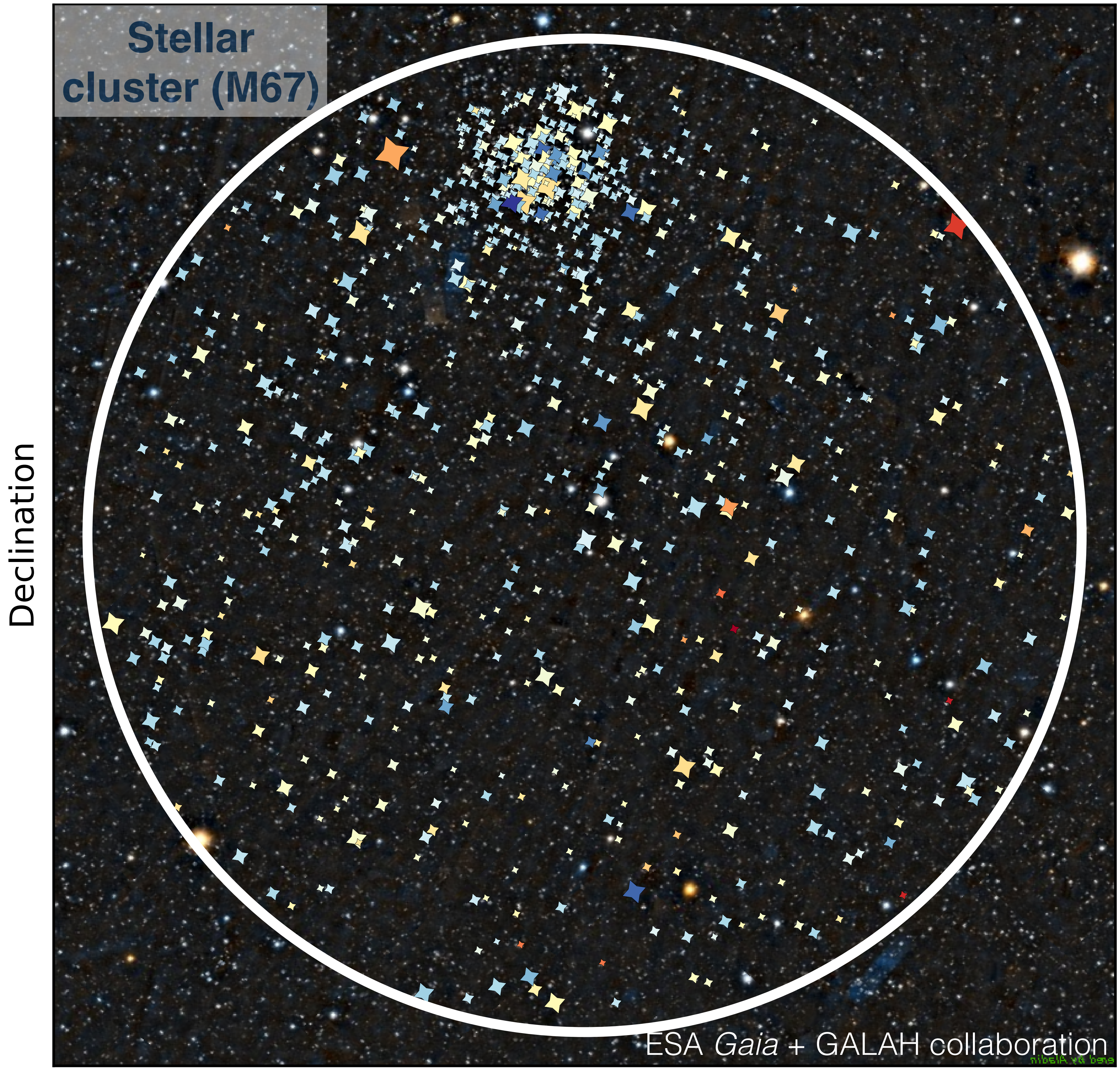
-> Galactic exploration

What do we know about our Galaxy already?

Stellar components of the Milky Way & their (chemodynamic) connection



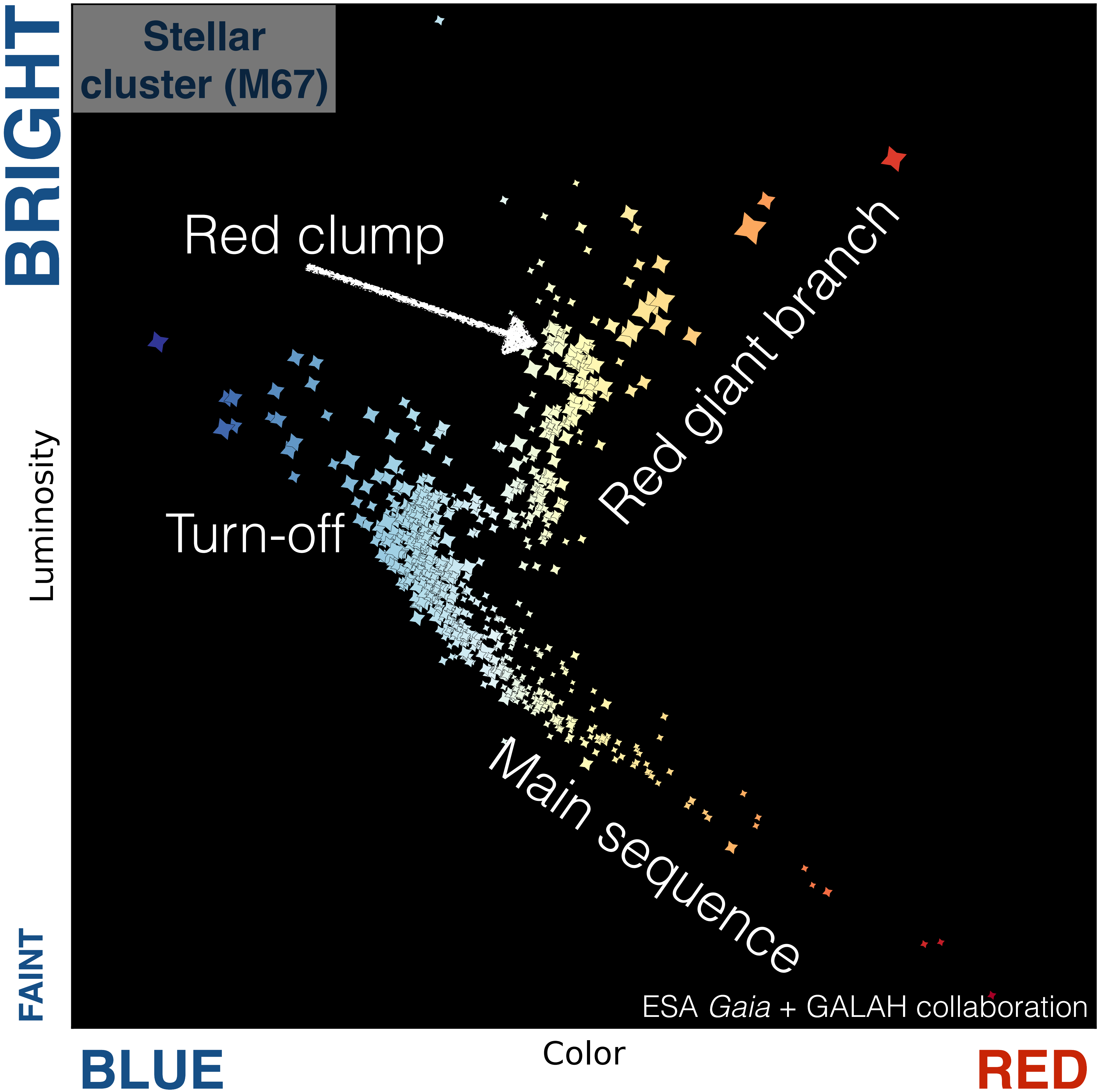
+
bar,
spiral arms,
radial migration,
accretion / mergers



Pan-STARRS collaboration

Stellar properties

Orbits (position+motion) -> astrometry



Stellar properties

Orbits
(position+motion)
-> astrometry

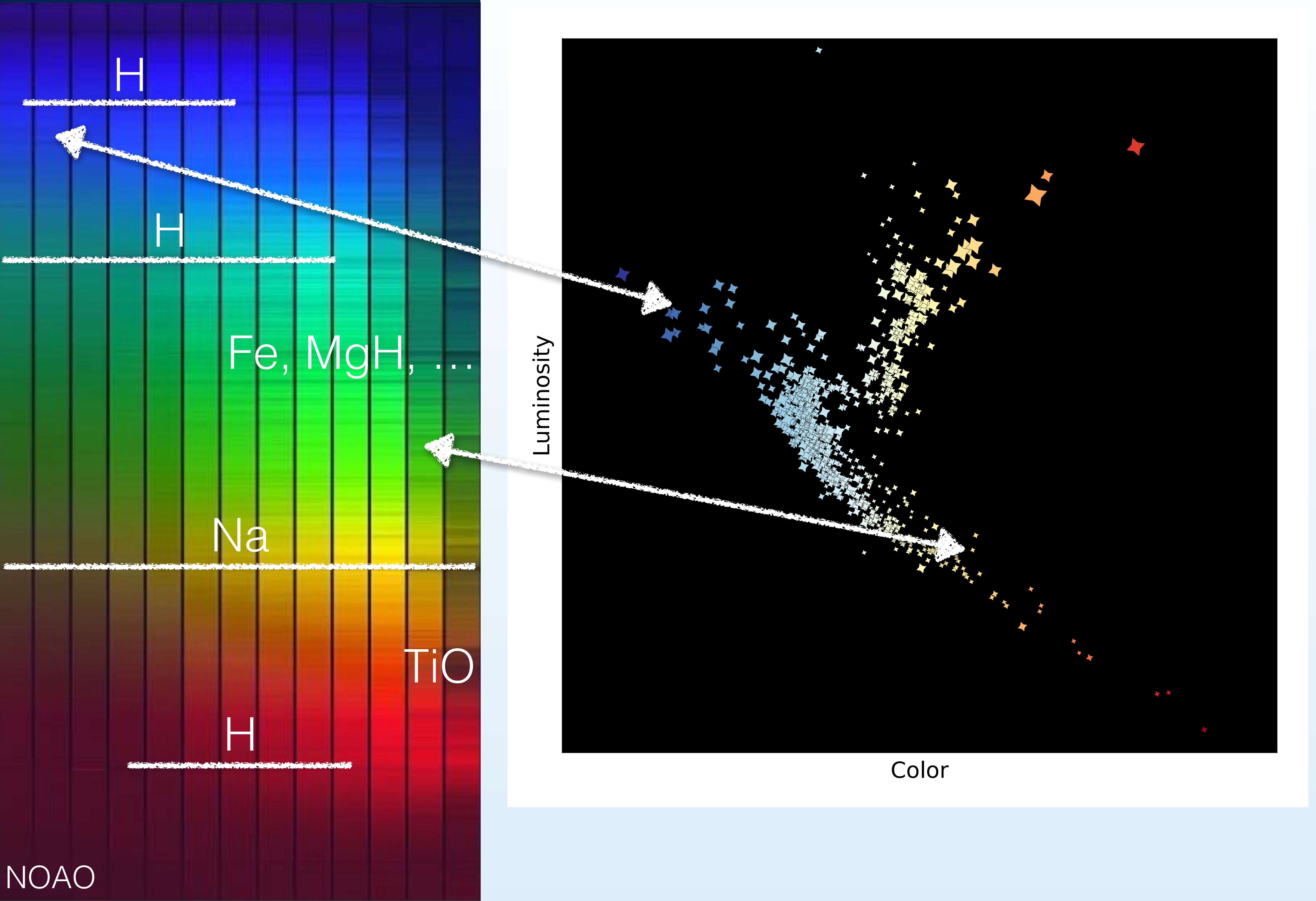
Color/temperature
-> photometry

Luminosity/gravity
-> photo- & astrometry

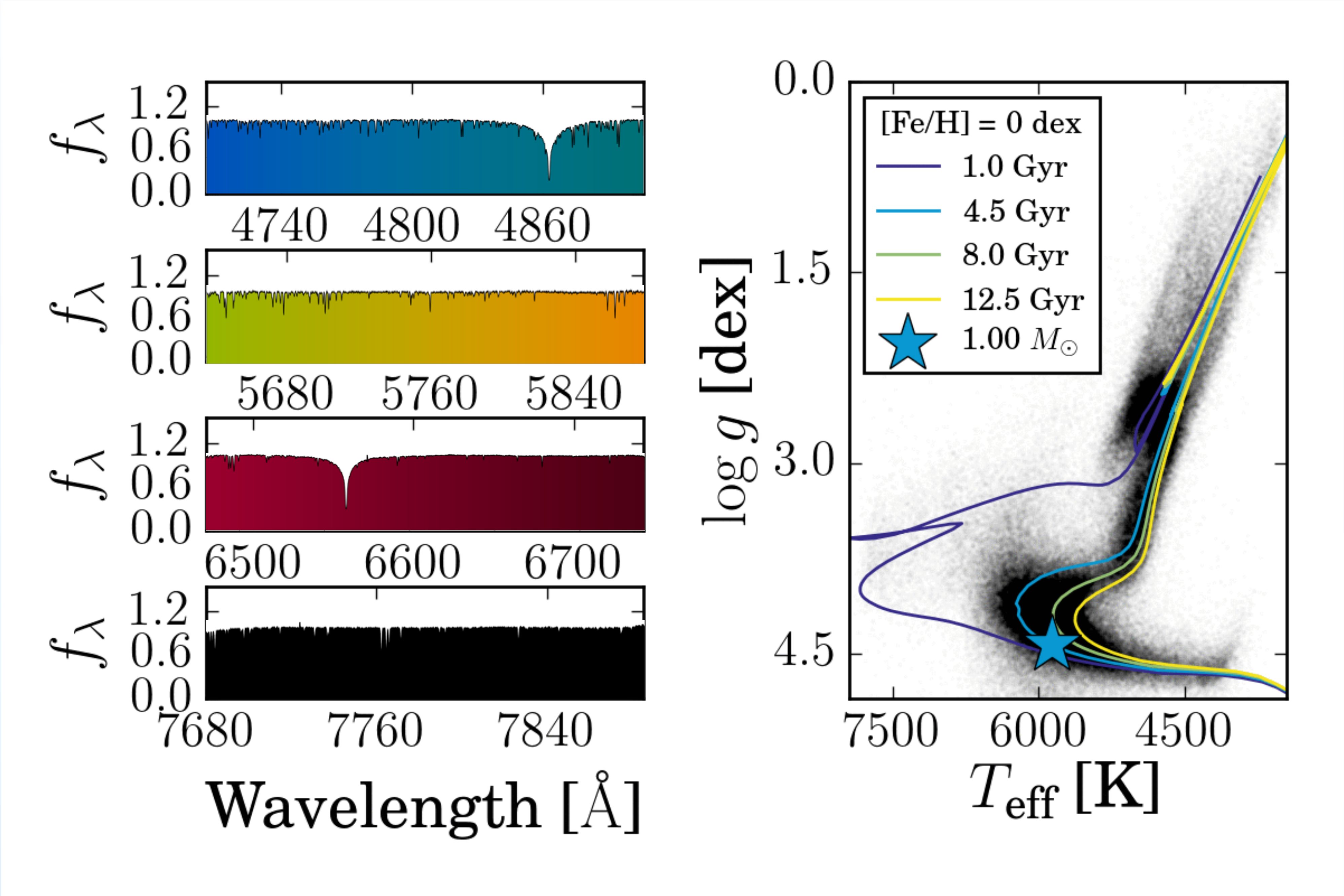
Stellar age
-> photo- & astrometry

Stellar mass/radius
-> photo- & astrometry

Hot —> Cool



Chemical Composition from Spectra



The information on the (chemical) composition of a star is hidden in its spectrum!

Surveys are the way to get data

(Q4) Which large-scale stellar spectroscopic surveys do you know?

Table 1.1: Stellar Spectroscopic Surveys of the Milky Way. The table is based on the collection by Rix & Bovy (2013) and Kollmeier et al. (2017) but was updated and extended. VIS stands for visible range, NIR for near-infrared and IR for infrared.

Survey	Magnitudes	Nr. Spectra	Resolution	Spectrograph
GCS (1)	$m_V \sim 10$	$2 \cdot 10^4$	20,000	CORAVEL (VIS)
SEGUE (2)	$15 \leq m_g \leq 20$	$4 \cdot 10^5$	2,000	SDSS-I/II (VIS)
RAVE (3)	$9 \leq m_i \leq 12$	$5 \cdot 10^5$	7,500	6dF (NIR)
LAMOST (4)	$m_G \leq 16$	$9 \cdot 10^6+$	1,800	LAMOST (VIS+NIR)
APOGEE (5)	$m_H \leq 12.2$	$4 \cdot 10^5+$	22,500	APOGEE (IR)
Gaia-ESO (6)	$m_V \leq 18$	$2 \cdot 10^5$	20,000 47,000	GIRAFFE (VIS+NIR) UVES (VIS)
Gaia RVS (7)	$m_G \leq 12$	$8 \cdot 10^6$	11,200	*Gaia* RVS (NIR)
GALAH (8)	$9 \leq V \leq 14$	$8 \cdot 10^5+$	28,000	HERMES (VIS+NIR)
WEAVE (9)	$m_G \leq 15.5$	$1 \cdot 10^6+$	5,000 20,000	WEAVE (VIS+NIR) WEAVE (VIS)
PFS (10)	$m_i \leq 23$	$1 \cdot 10^6+$	3,000	PFS (VIS+NIR)
DESI (11)	$m_r \leq 23$	$1 \cdot 10^6+$	5,000	DESI (VIS+NIR)
MOONS (12)	$m_g \leq 22$ $m_H \leq 17$	$2 \cdot 10^6$	5,000 20,000	VIS+NIR+IR) WEAVE (VIS)
4MOST (13)	$m_G \leq 20.5$	$16 \cdot 10^6+$ $3 \cdot 10^6+$	6,500 20,000	LRS (VIS+NIR) HRS (VIS)
SDSS-V (14)	$m_H \leq 13.4$ $m_i \leq 20$	$7 \cdot 10^6$	22,000 2,000	APOGEE (IR) BOSS (VIS+NIR)
MSE (15)	$m_g \leq 24$	10^6++	$\leq 40,000$	MSE (VIS+NIR)

Notes: (1) see e.g. Nordström et al. (2004), (2) see e.g. Yanny et al. (2009), (3) see e.g. Steinmetz et al. (2006), (4) see e.g. Cui et al. (2012), (5) see e.g. Allende Prieto et al. (2008); Majewski et al. (2016), (6) see e.g. Gilmore et al. (2012), (7) see e.g. Cropper et al. (2018); Katz et al. (2019) (8) see e.g. De Silva et al. (2015), (9) see e.g. Dalton et al. (2016), (10) see e.g. Takada et al. (2014), (11) see e.g. DESI Collaboration et al. (2016), (12) see e.g. Cirasuolo et al. (2014), (13) see e.g. de Jong et al. (2019), (14) see e.g. Kollmeier et al. (2017), (15) see e.g. Bergemann et al. (2019)..

Attempt of a collection: My PhD Thesis

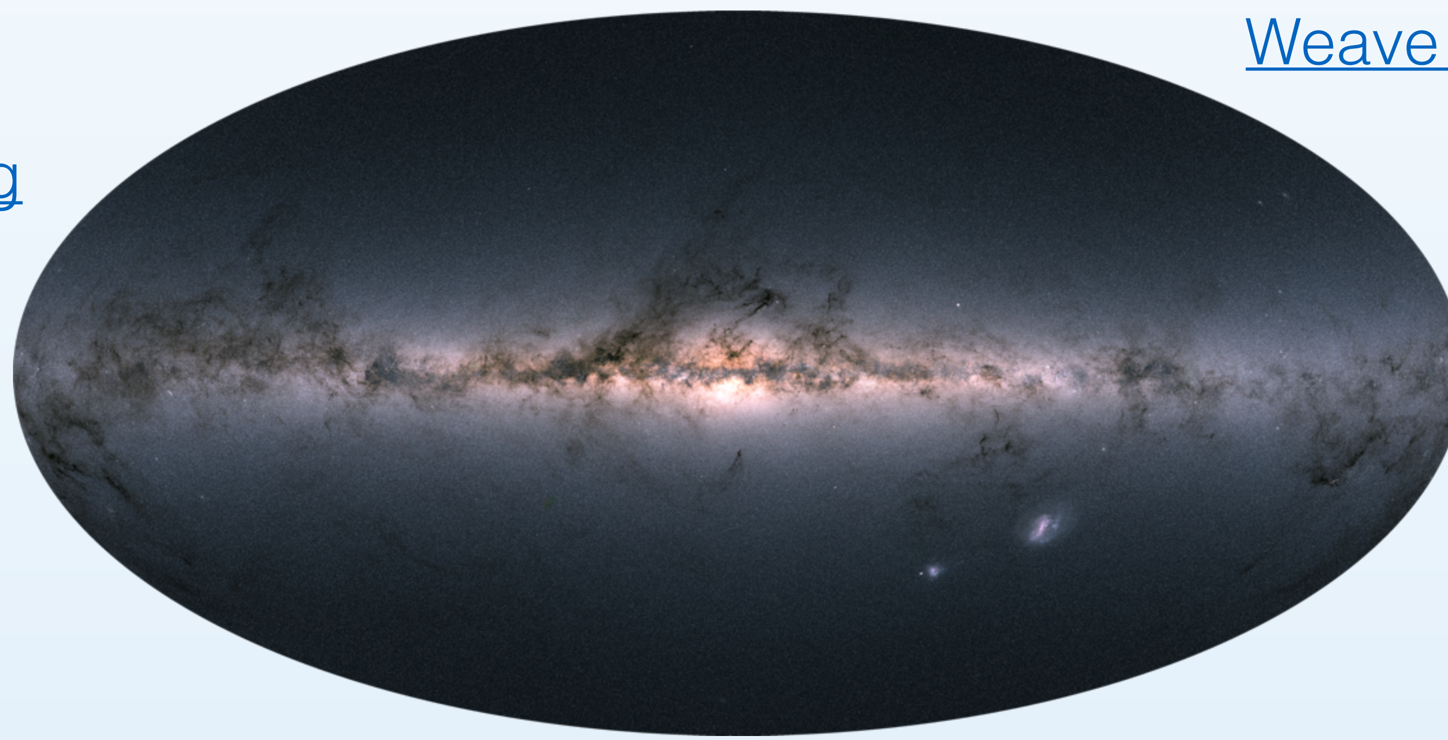
Surveys are the way to get data

(Q4) Which large-scale stellar spectroscopic surveys do you know?

galah-survey.org

www.rave-survey.org

Weave website



www.4most.eu

www.gaia-eso.eu

. . .

www.sdss.org

Surveys are the way to get data

(Q4) Which large-scale stellar spectroscopic surveys do you know?

(Q5) What is the most important characteristic of any large survey?

(Q6) What do you think is the biggest limitation of current surveys?

Large-scale stellar spec. surveys

public, automated, large amounts of data/person power/obs runs

RAVE, *Gaia*-ESO, GALAH, LAMOST, APOGEE, WEAVE, 4MOST, SDSS-V, *Gaia* RVS, …

&

their limitations

Coverage:
- observation time / distance / magnitude
- FoV / pencil beam / multiplexing
- spectral quality (R vs. λ vs. S/N vs. No)

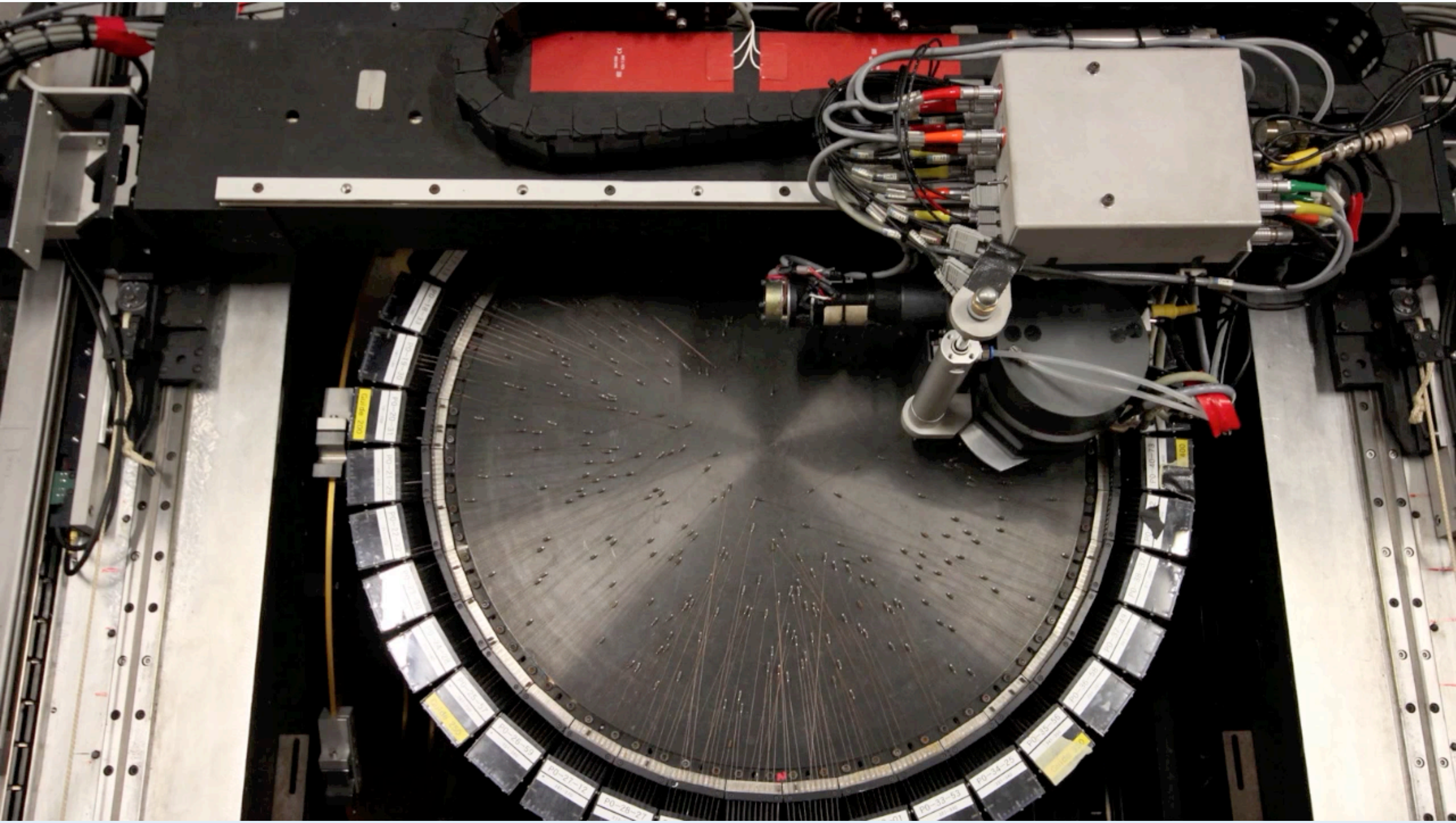
Data flow / logistics:
- automated big data analysis
- accuracy & precision

Where are these surveys operating

1	Gaia RVS (L2)	4	WEAVE (La Palma, Spain)
2	APOGEE* (Apache Point, USA)	5	LAMOST (Xinglong, China)
3	Gaia-ESO/4-MOST (Paranal, Chile)	6	GALAH/RAVE (Siding Spring, Australia)

 *APOGEE is now also observing from Las Campanas Observatory (Chile)

How do surveys observe so many stars?

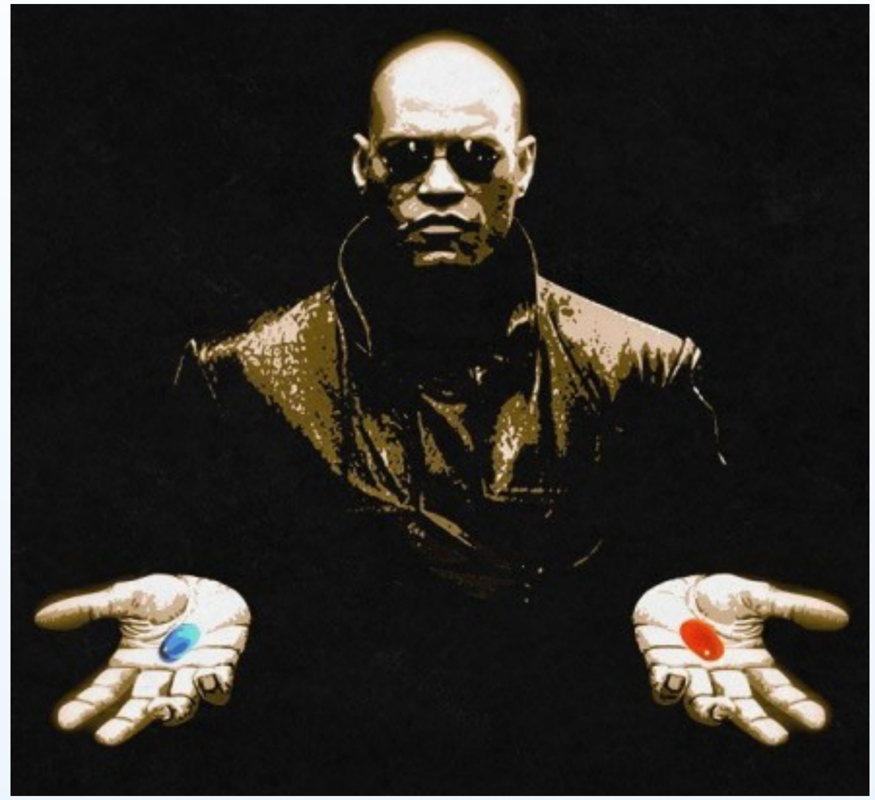


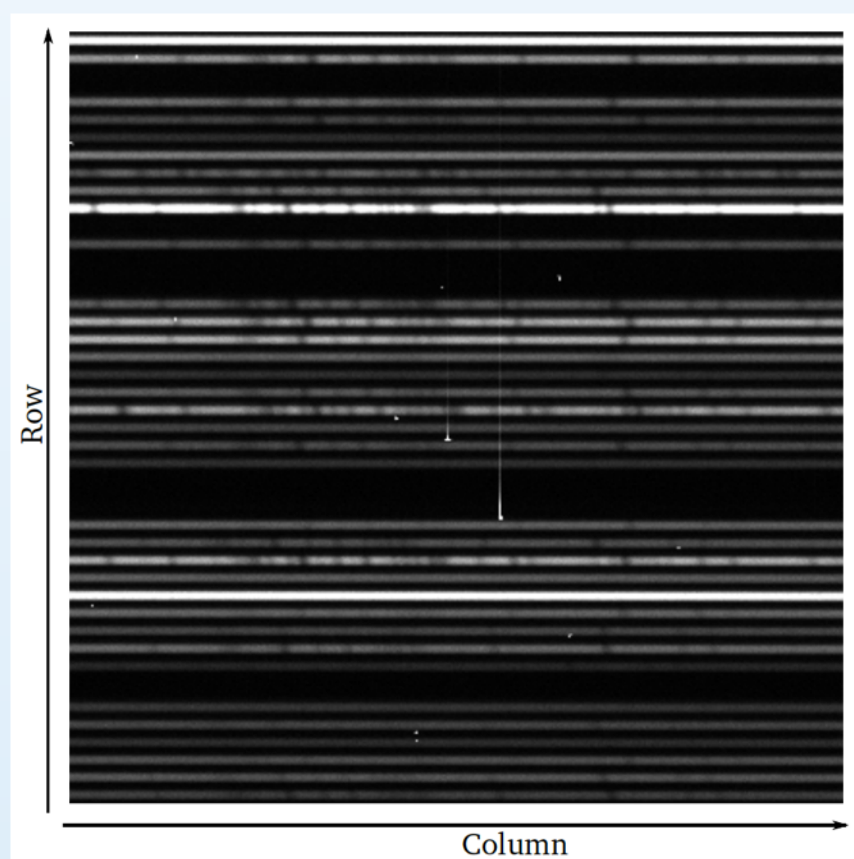
A 2dF night at AAT: https://www.youtube.com/watch?v=qOtkI4HYzTk

Sven Buder (MPIA)

Stellar properties from CCD images

The easy way	**The right way**
fibre == px row & col	fibre == CCD model
single star / fibre	stellar system / fibre
no time-domain	time domain
1D LTE	3D non-LTE
independent labels	label dependencies
…	…

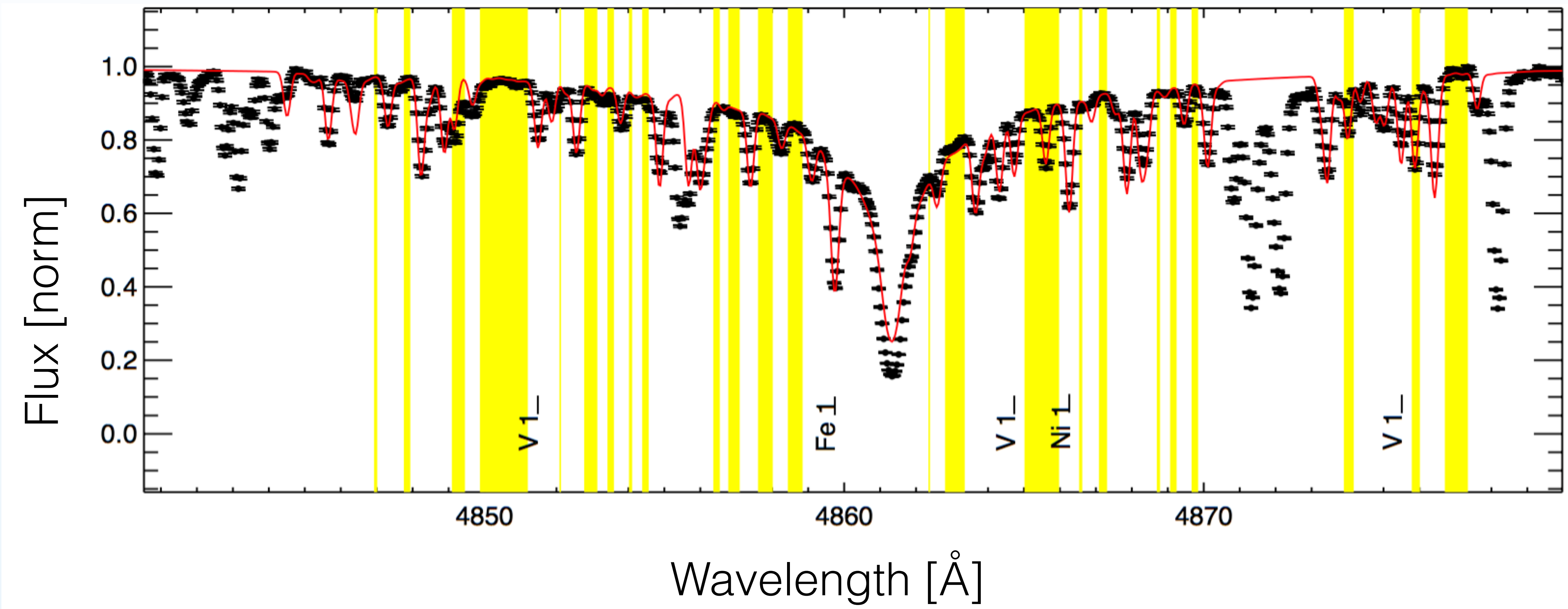




Stellar properties from spectra

Annie Jump Cannon classified ~340,000 stars in her career (50 per hour, not including chemical composition!)

“Model-driven” Stellar properties from spectra



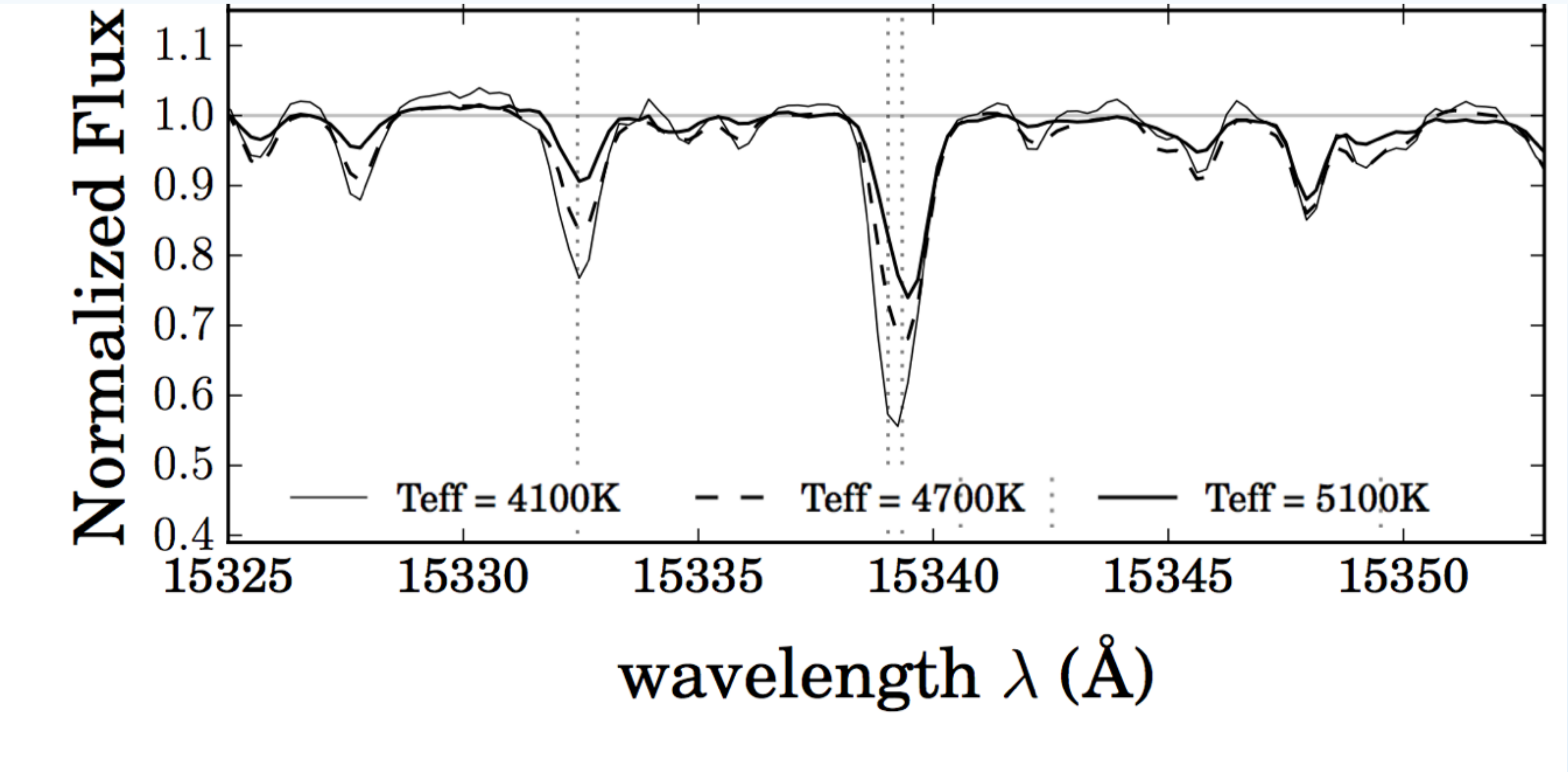
Spectrum synthesis based on atmosphere models
(molecular+ionisation equilibrium, continuous+line opacities, radiative transfer)

χ^2 **optimisation** of stellar parameters and element abundances

Ask Alvin, Laia or me or see for example:
Spectroscopy Made Easy by Piskunov & Valenti (2017)
http://adsabs.harvard.edu/abs/2017A%26A...597A..16P

“Data-driven” stellar properties from spectra

Use linear algebra (e.g. quadratic model) to construct spectral flux **f** from stellar labels *l* (temperature, metallicity, …)



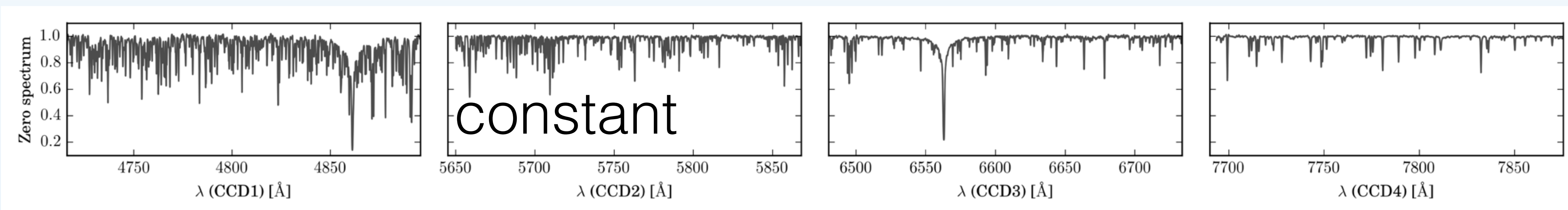
This works because stellar flux varies smoothly with varying labels -> we can parametrise this change

see for example: The Cannon by Ness et al. (2015)
http://adsabs.harvard.edu/abs/2015ApJ...808...16N

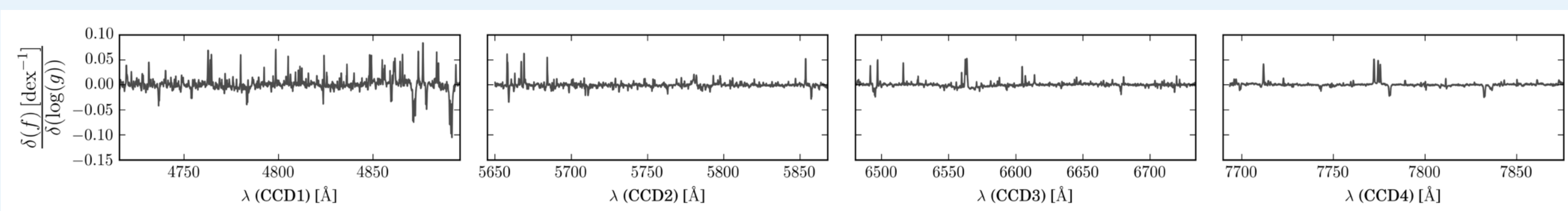
"Data-driven" stellar properties from spectra

Use linear algebra (e.g. quadratic model) to construct spectral flux **f** from stellar labels *l* (temperature, metallicity, …)

$$\boxed{\mathrm{f}_{n,\lambda} = \Theta_\lambda^T \cdot l_n + \text{noise}}$$



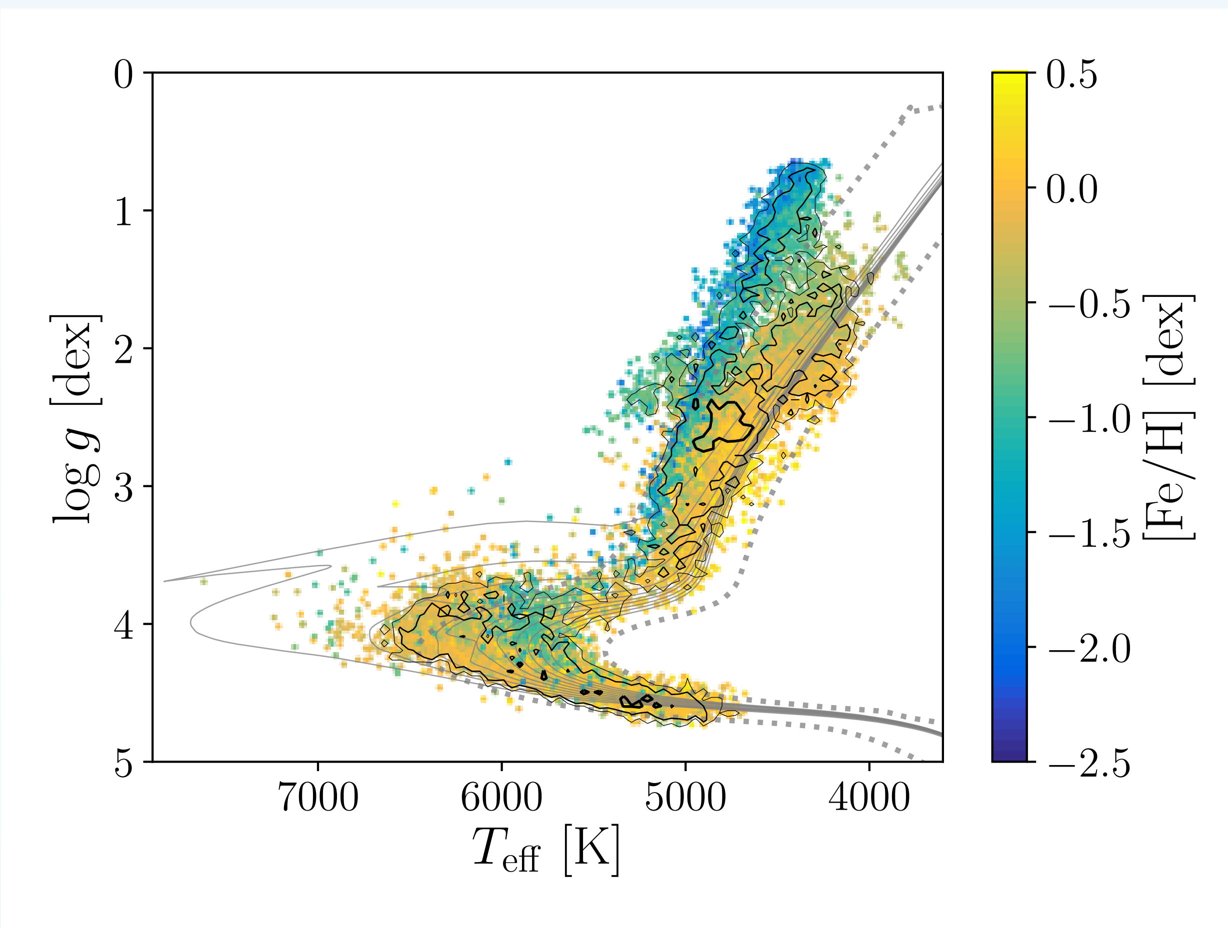
linear coefficient for surface gravity:



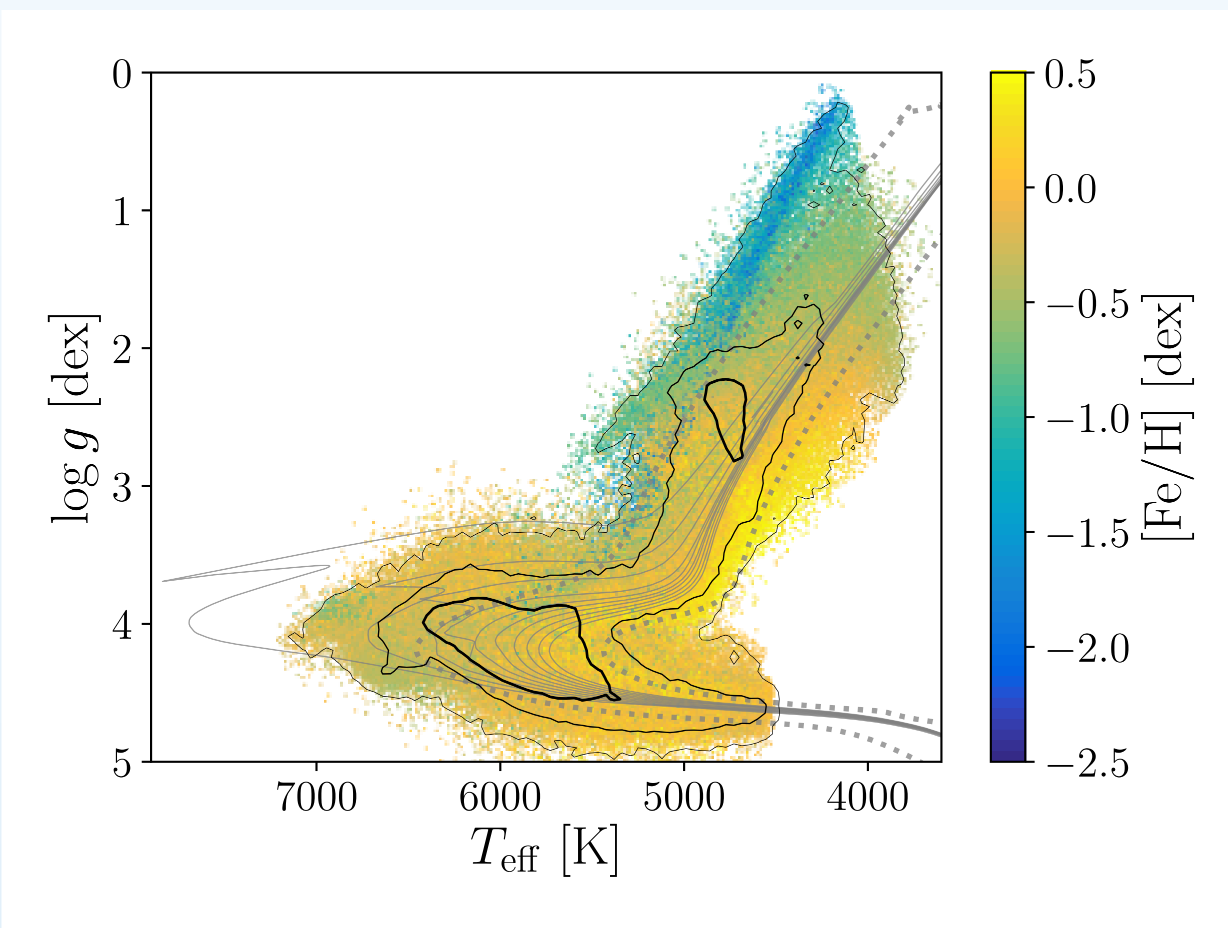
"Data-driven" stellar properties from spectra

Use linear algebra (e.g. quadratic model) to construct spectral flux **f** from stellar labels l (temperature, metallicity, ...)

$$\mathrm{f}_{n,\lambda} = \Theta_\lambda^T \cdot l_n + \text{noise}$$



l_n fixed, train Θ_λ

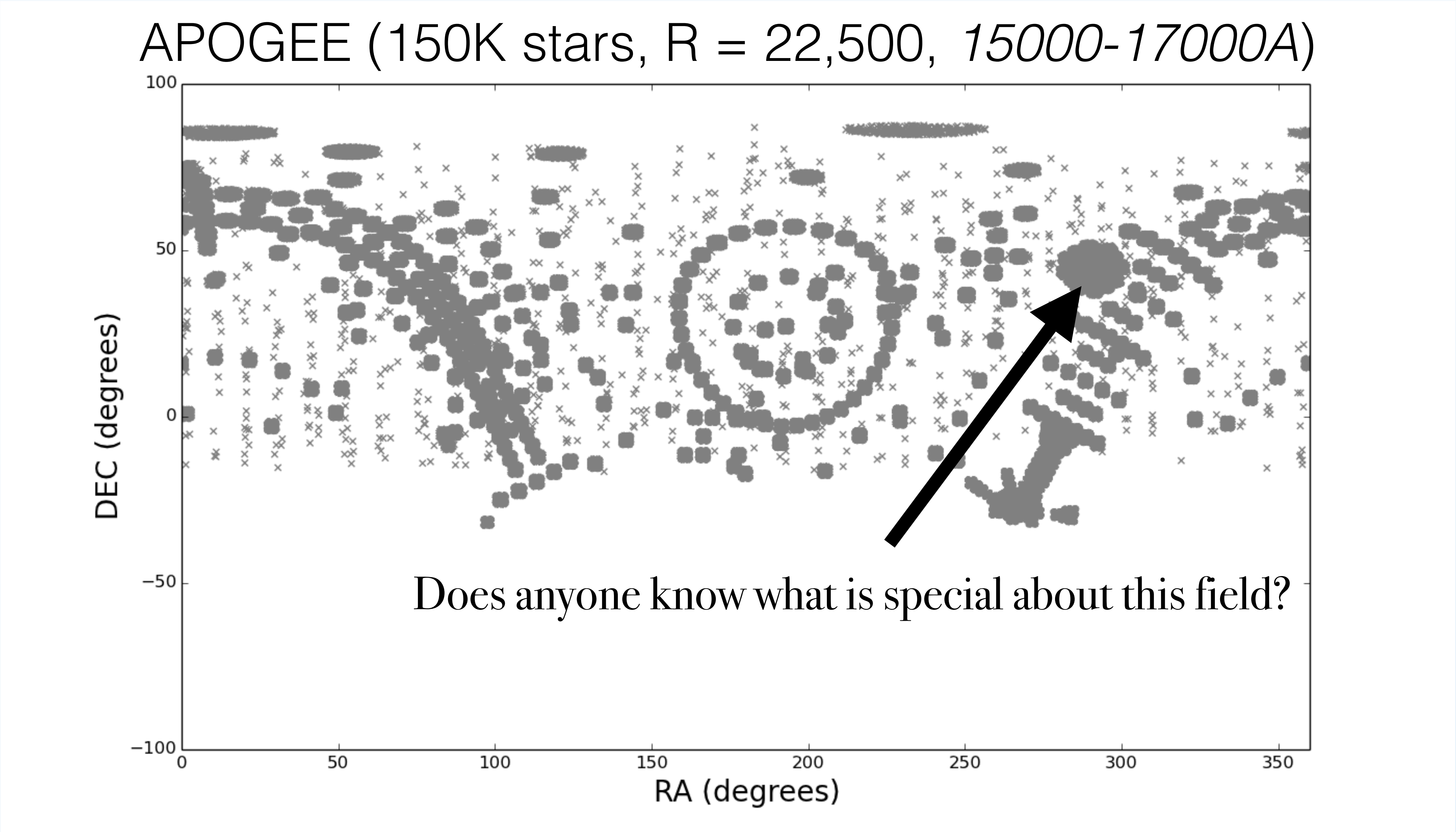


Θ_λ fixed, optimise l_n in 0.1s

Sven Buder (MPIA)

The industrial revolution of Galactic Archaeology

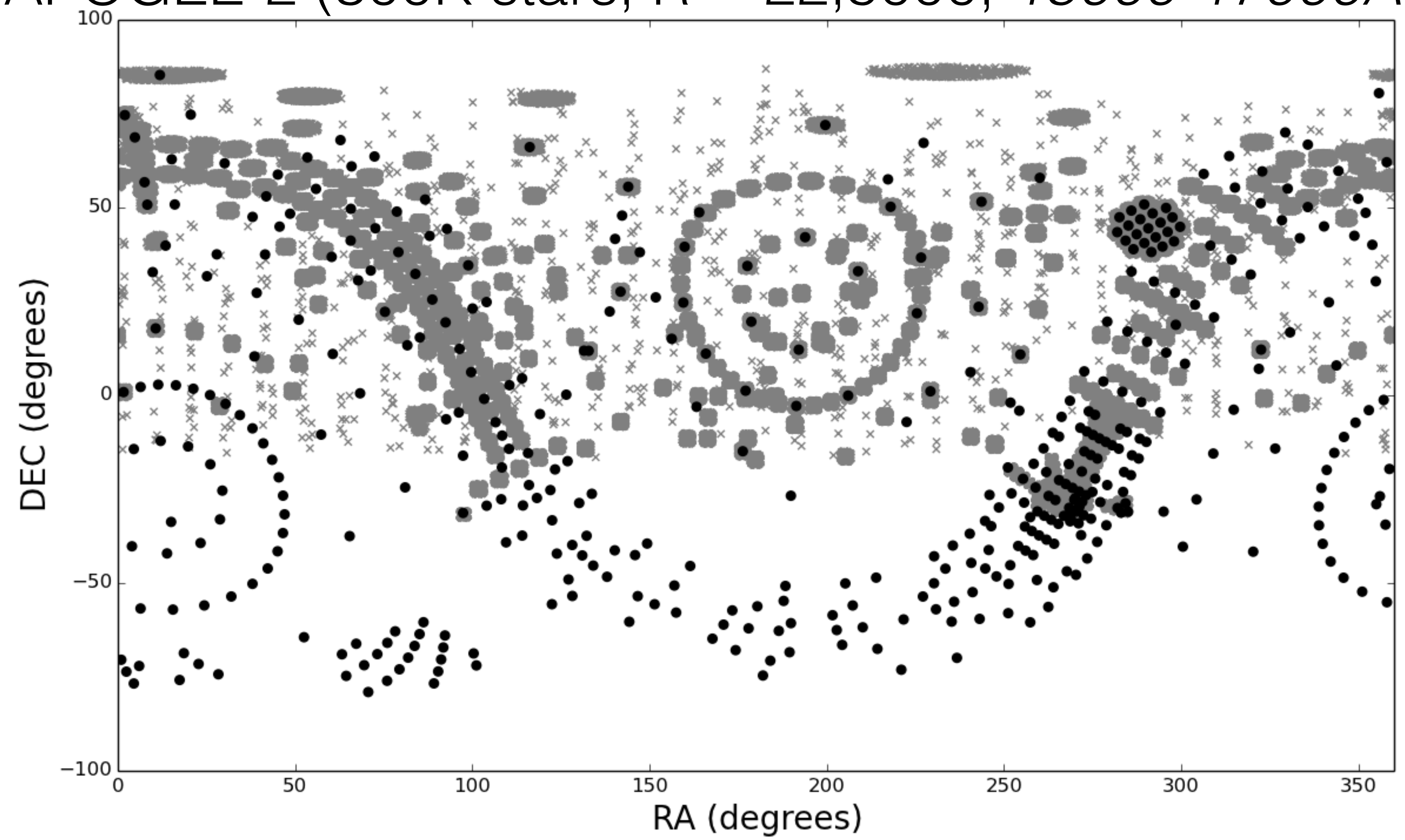
- Multitude of surveys at different R, λ, (l,b)
- Independent pipelines for parameters



THE INDUSTRIAL REVOLUTION OF GALACTIC ARCHAEOLOGY

- Multitude of surveys at different R, λ, (l,b)
- Independent pipelines for parameters

APOGEE-2 (300K stars, R = 22,5000, *15000-17000A*)



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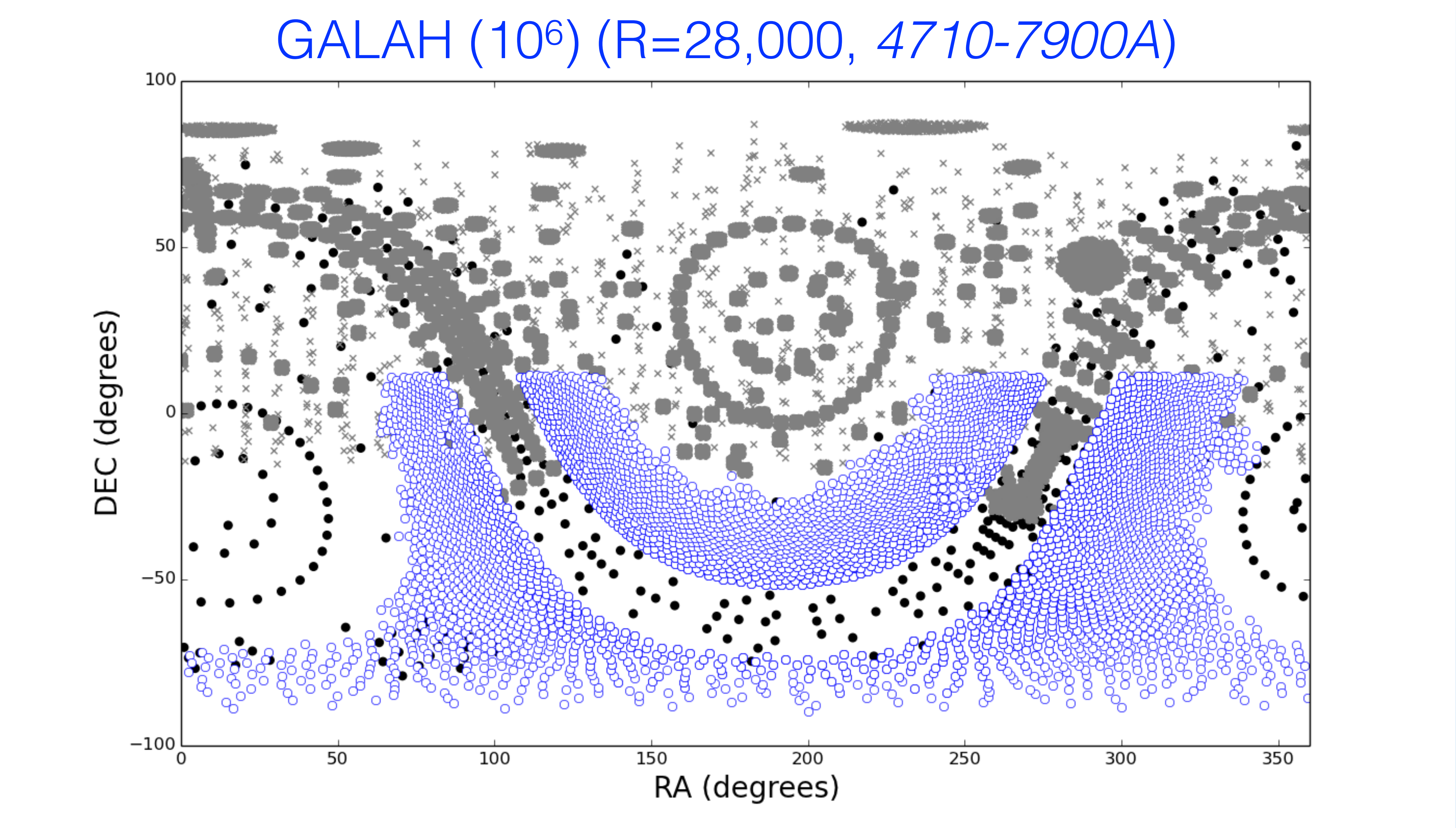

The industrial revolution of Galactic Archaeology

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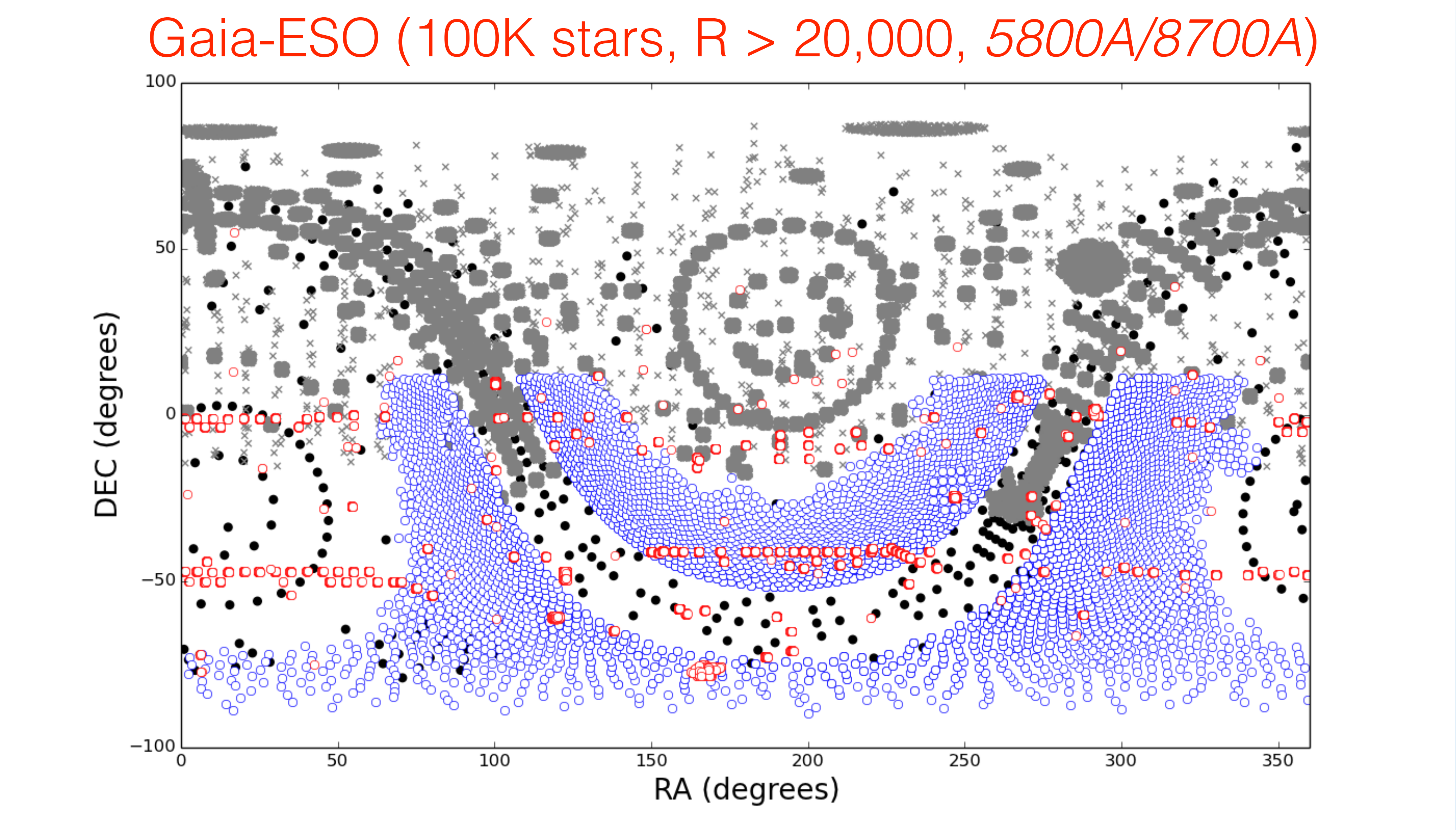
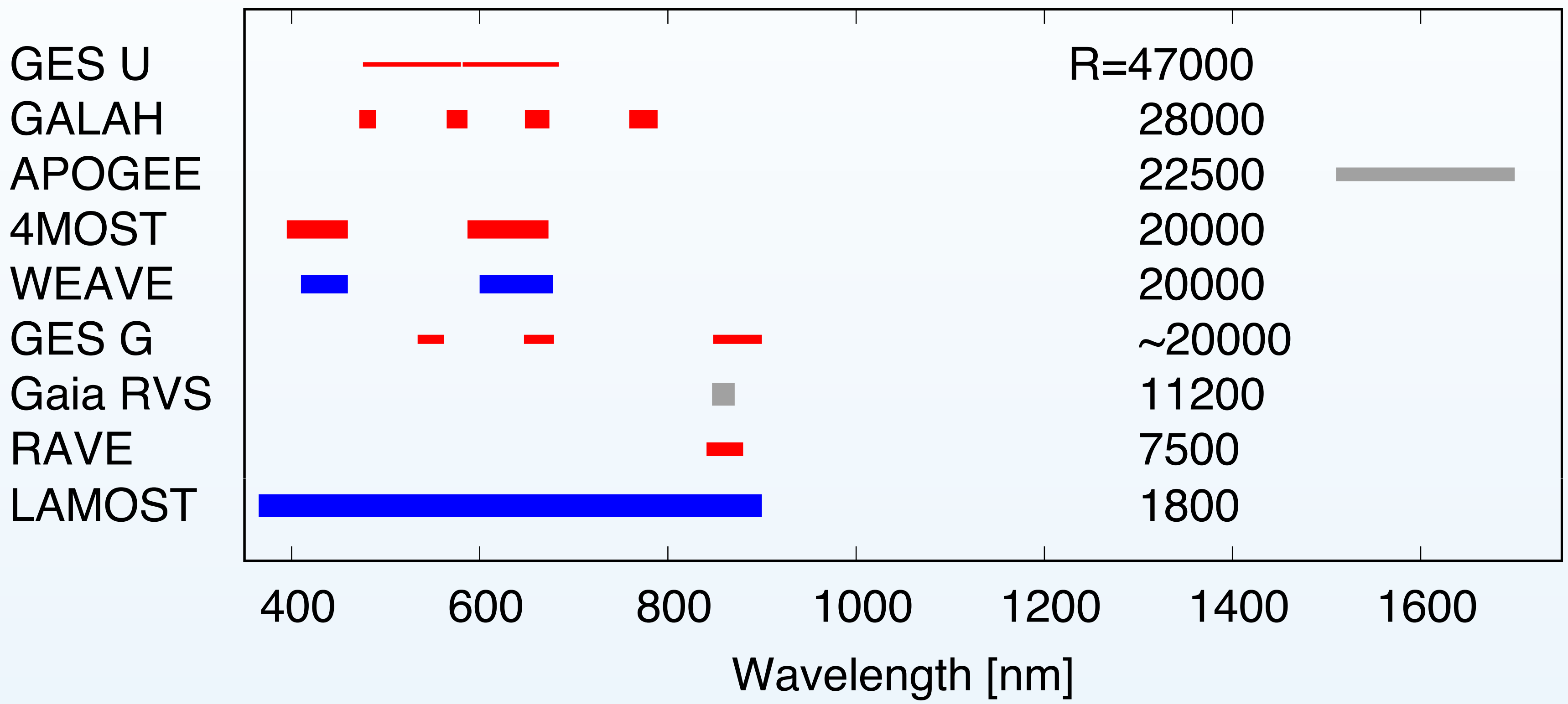


Does anyone know why all the fields are circles?

The industrial revolution of Galactic Archaeology



Jofré+2018
http://adsabs.harvard.edu/abs/2018arXiv181108041J

- There is so much **opportunity** [Gaia+spectroscopic surveys] to use stars as tools to understand the Milky Way's formation and evolution
- Millions of spectra exist for which there are upwards of 30 measurements (abundances, multiple radial velocities, proper motions, time-variability]
- Fundamental empirical characteristics like the relationship between stellar **orbits** and stellar **abundances** and stellar **age** is only just beginning to be examined

APOGEE

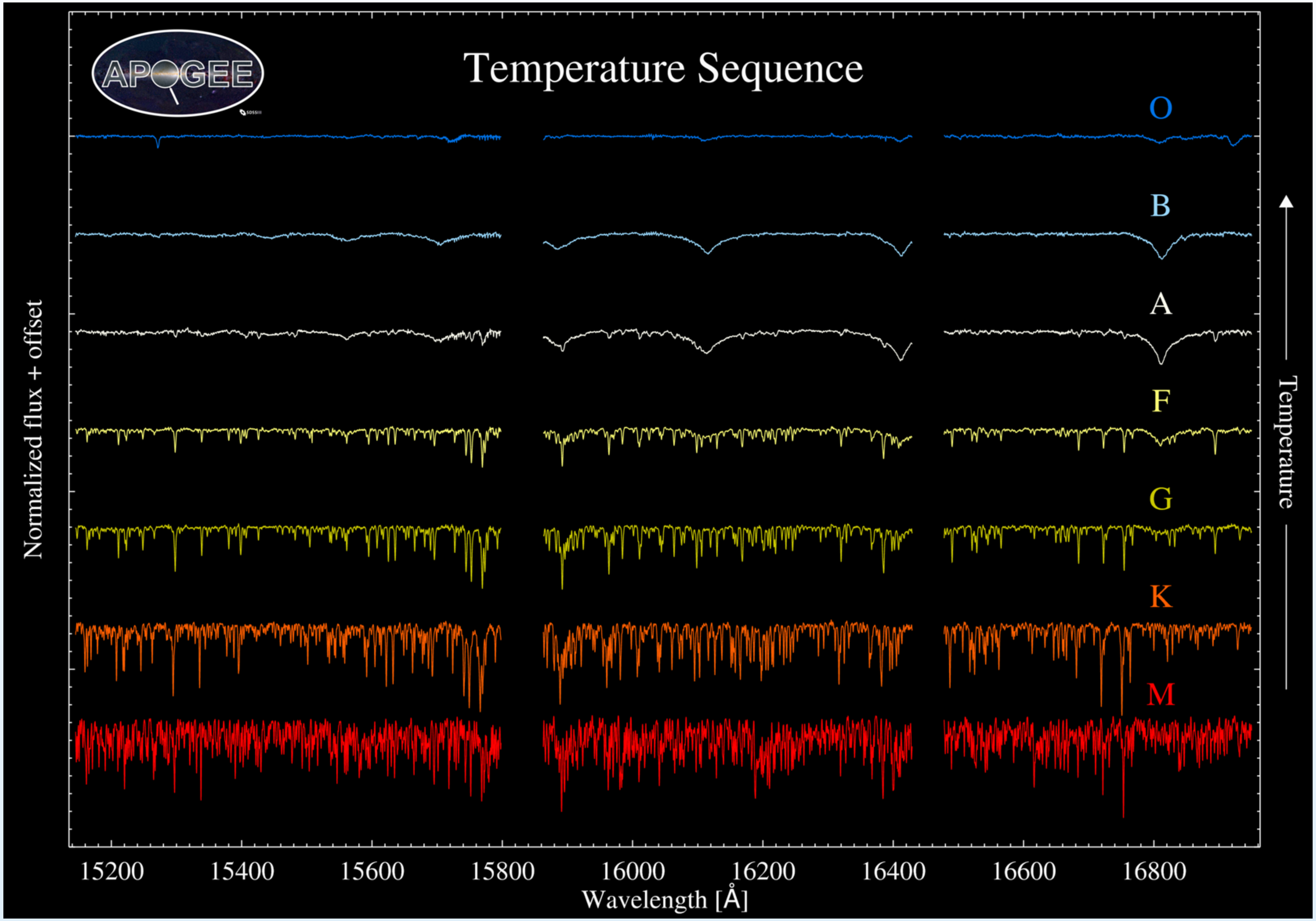
Apache Point Observatory Galactic Evolution Experiment

Setup	IR (1.51-1.70μm), R 20,000 Teff, logg, [M/H], and 20 abundances
MW	bulge, disk, halo in the previously unexamined dust obscured regions
Aim	MW formation via understanding all of the main components up to 500,000 stars until 2020 (annual DR's)

- Public spectra, public models and linelist, well documented catalogue
- Two stellar parameter & abundance catalogues, *ASPCAP* and *The Cannon*
- Most stars have many return visits (multiple epochs of radial velocities)
- Science - data-driven modeling pioneered on this spectra, feasibility of chemical tagging evaluated – ultimate Milky Way mapping experiment to now

APOGEE

Apache Point Observatory Galactic Evolution Experiment



APOGEE

https://www.sdss.org/dr14/irspec/spectro_data/

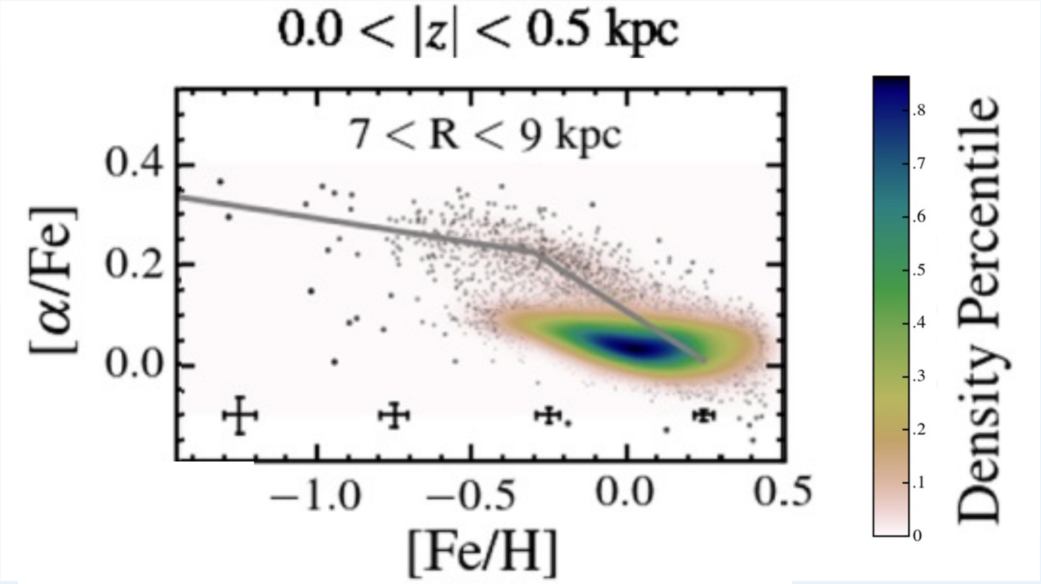
Catalog Data

Contents	SAS Location	CAS Table
catalog of ASPCAP stellar parameters and abundances	allStar-l31c.2.fits (in APOGEE_REDUX; see datamodel)	aspcapStar
catalog of *Cannon* stellar parameters and abundances	allStarCannon-l31c.2.fits (in APOGEE_REDUX; see datamodel)	cannonStar
catalog of stellar properties from combined spectra (e.g., RVs)	allStar-l31c.2.fits (in APOGEE_REDUX; see datamodel)	apogeeStar
catalog of properties from individual visit spectra	allVisit-l31c.2.fits (in APOGEE_REDUX; see datamodel)	apogeeVisit

DR16 (Dec) will be almost 500K stars inc. main sequence (currently 300K stars and only giants)

Advances with APOGEE - Chemical cartography

Chemical Cartography with APOGEE: Metallicity Distribution Functions and the Chemical Structure of the Milky Way Disk – **Hayden+ 2015**
http://adsabs.harvard.edu/abs/2015ApJ...808..132H



Solar vicinity

ADVANCES WITH APOGEE - CHEMICAL CARTOGRAPHY

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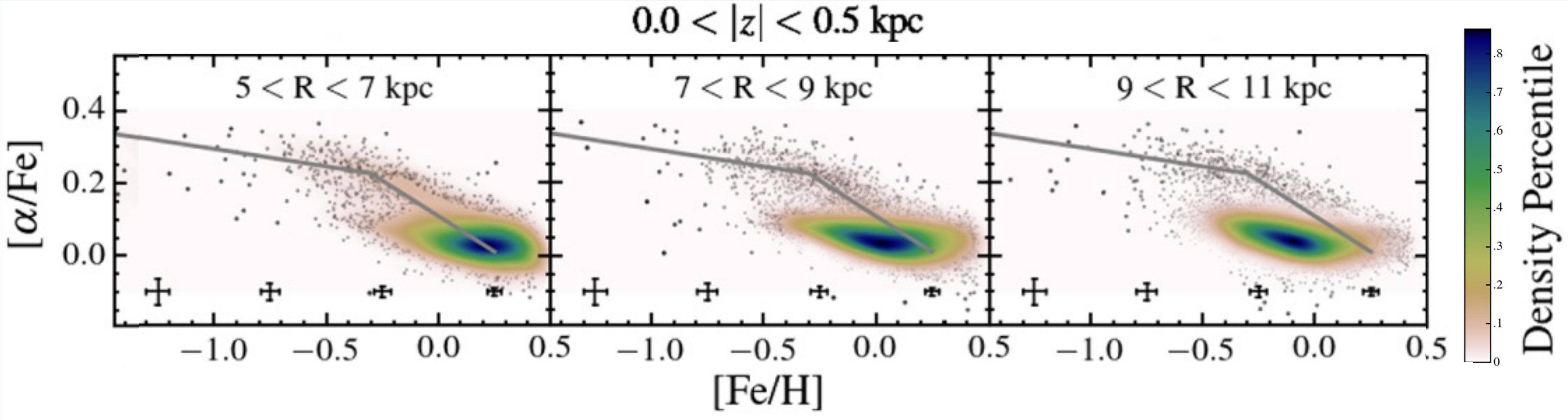

Inner disk Solar vicinity Outer disk

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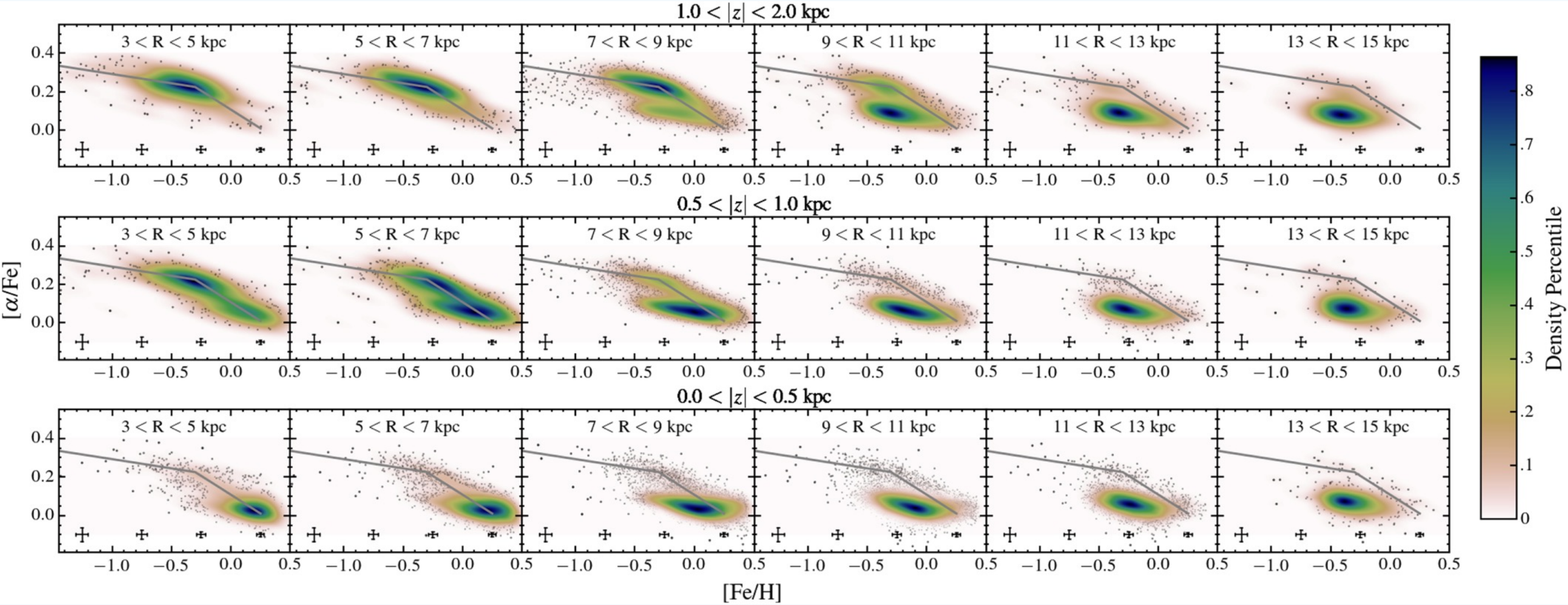

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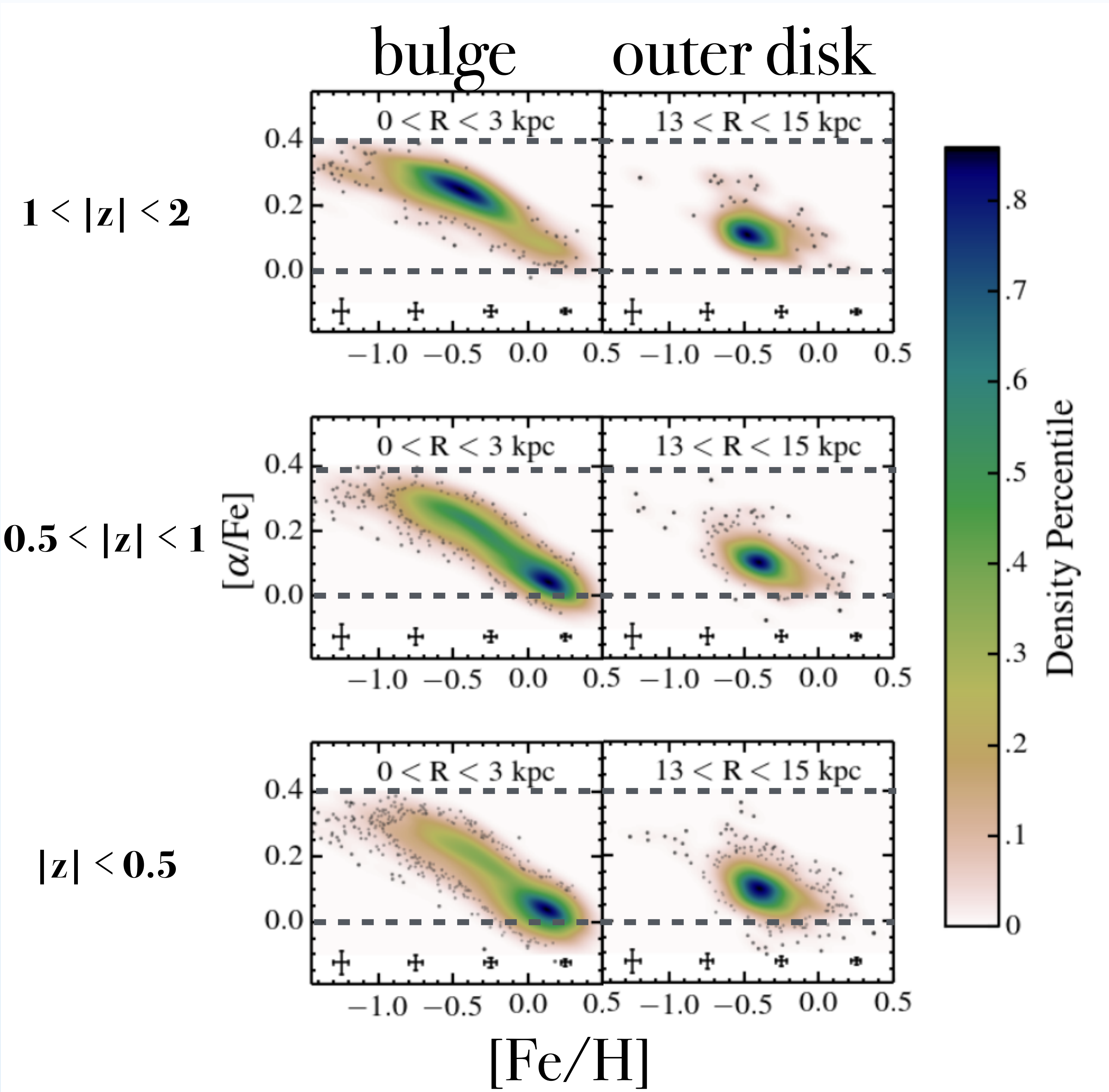
Advances with APOGEE - Chemical cartography

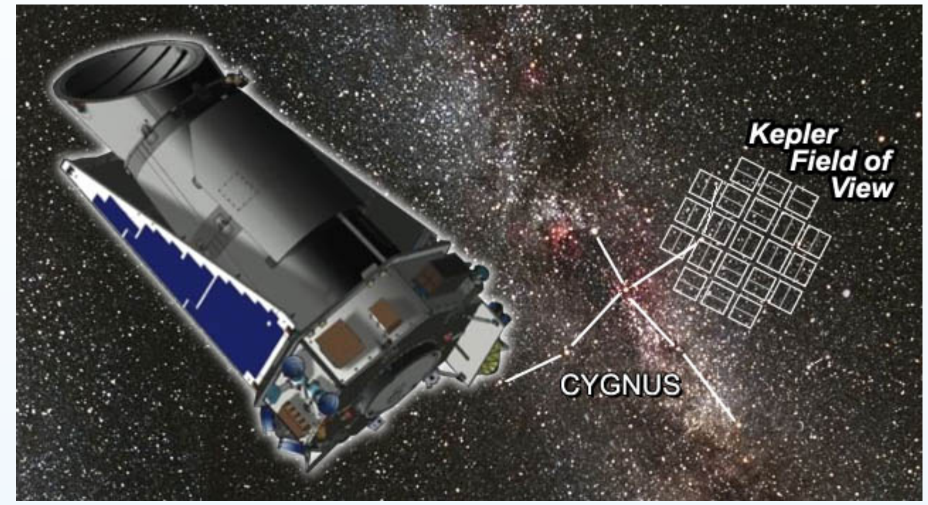


- inner region dominated by high-α, outer region by low-α sequence
- bulge reaches both lower and higher [Fe/H] than outer disk
- narrow & high α-sequence in inner region: high star formation rate in early epoch in disk (from which the bulge formed)
- low [α/Fe] in outer region: slower later star formation from enriched gas

Figure made by M. Hayden (USyd)

Advances with APOGEE - Spectroscopy + Asteroseismology

+



- **APOKASC** – stars observed by both APOGEE & Kepler

Stellar oscillations probe internal structure of the star

Pinsonneault+ 2018 https://arxiv.org/abs/1804.09983 – The Second APOKASC Catalog: The Empirical Approach

http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=J/ApJS/239/32

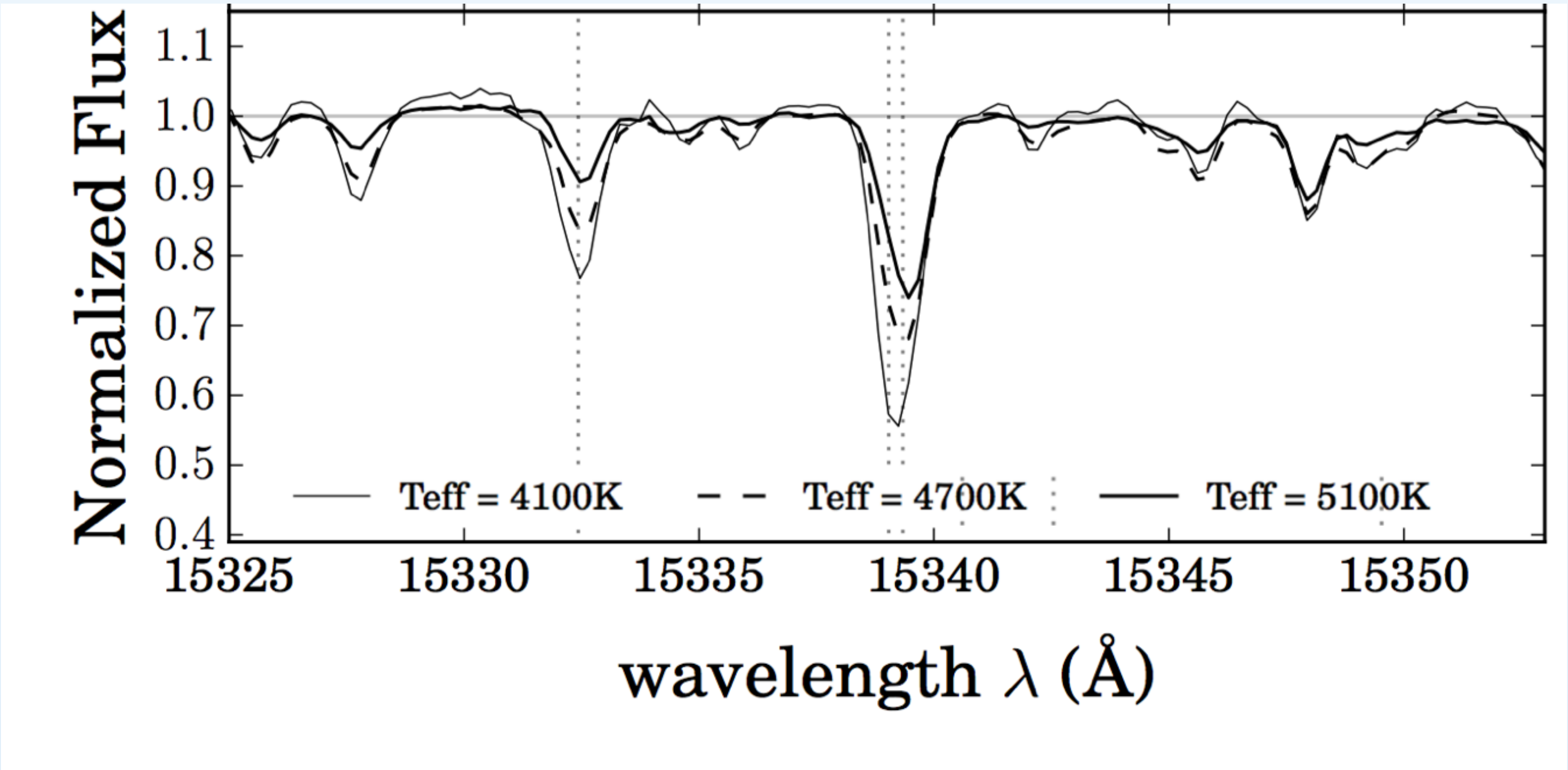
- 16,000 stars: evolutionary state, surface gravity, mean density, mass, radius, age, and the spectroscopic and asteroseismic measurements used to derive them

or have a chat with Amalie

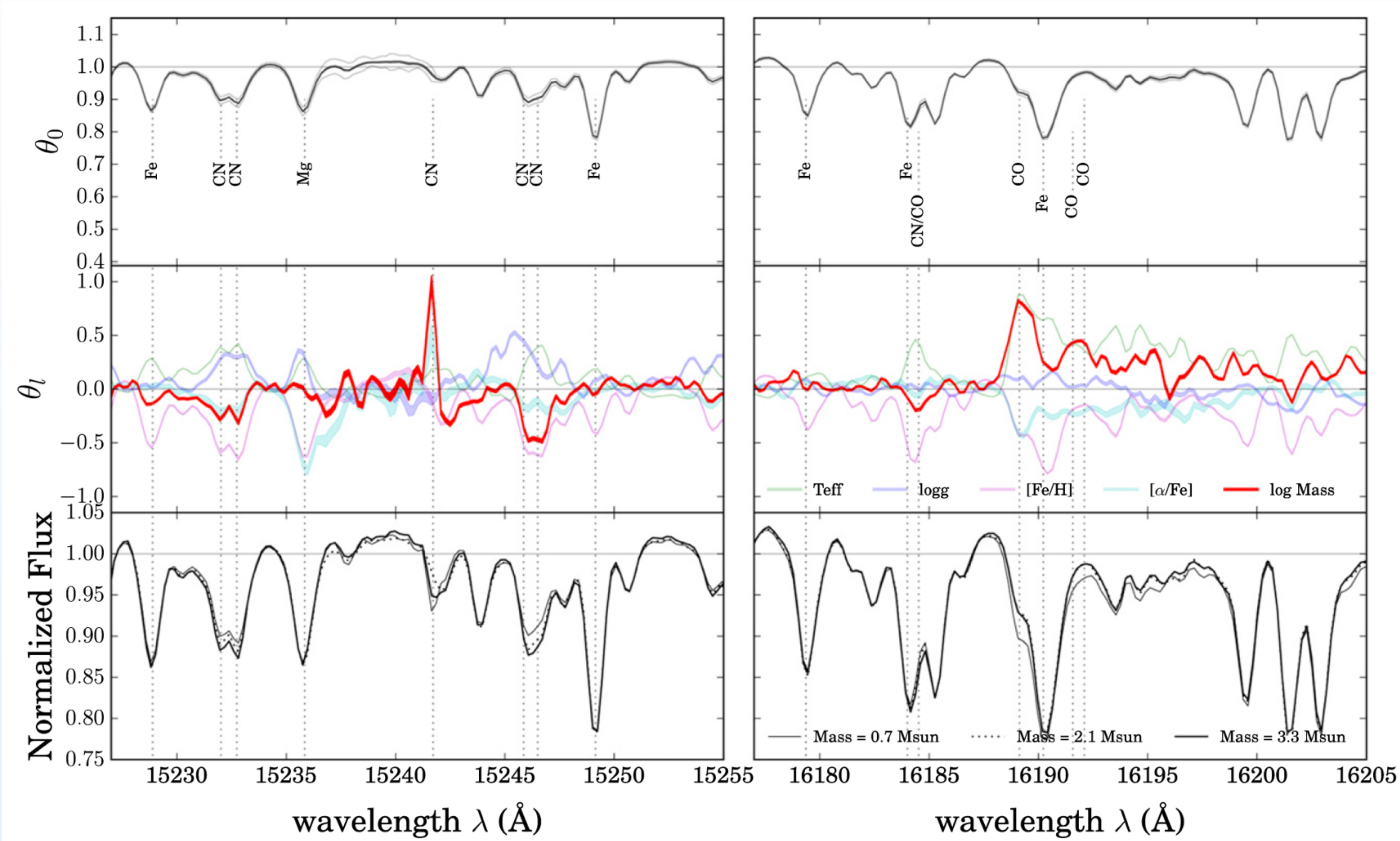
Advances with APOGEE — data-driven models

The Cannon: A data-driven approach to Stellar Label Determination
– **Ness+ 2015 (put all surveys on the same scale using stars in common)**
http://adsabs.harvard.edu/abs/2015ApJ...808...16N

Spectroscopic Determination of Masses (and Implied **Ages**) for Red Giants –
Ness+ 2016 (train a model on APOKASC propagate to all spectra), Martig+2016
http://adsabs.harvard.edu/abs/2016ApJ...823..114N



Advances with APOGEE — Stellar ages for giants

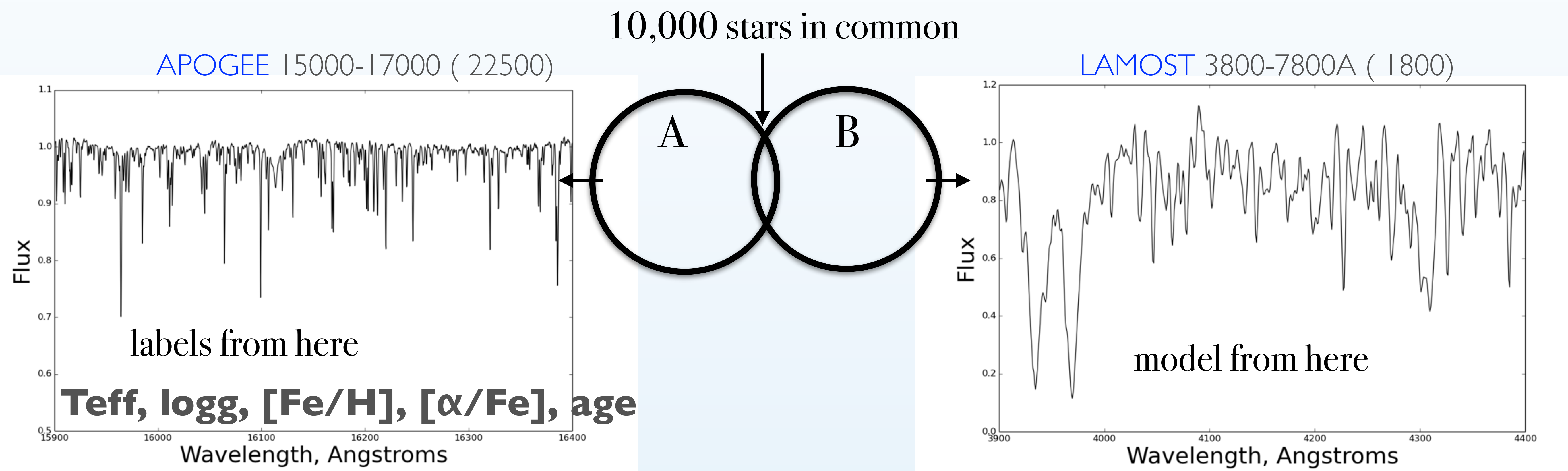


CNO abundances of giants correlate with stellar mass/age!

Martig+16: http://adsabs.harvard.edu/abs/2016MNRAS.456.3655M

Ness+16: http://adsabs.harvard.edu/abs/2016ApJ...823..114N

Advances with APOGEE — Stellar ages for giants



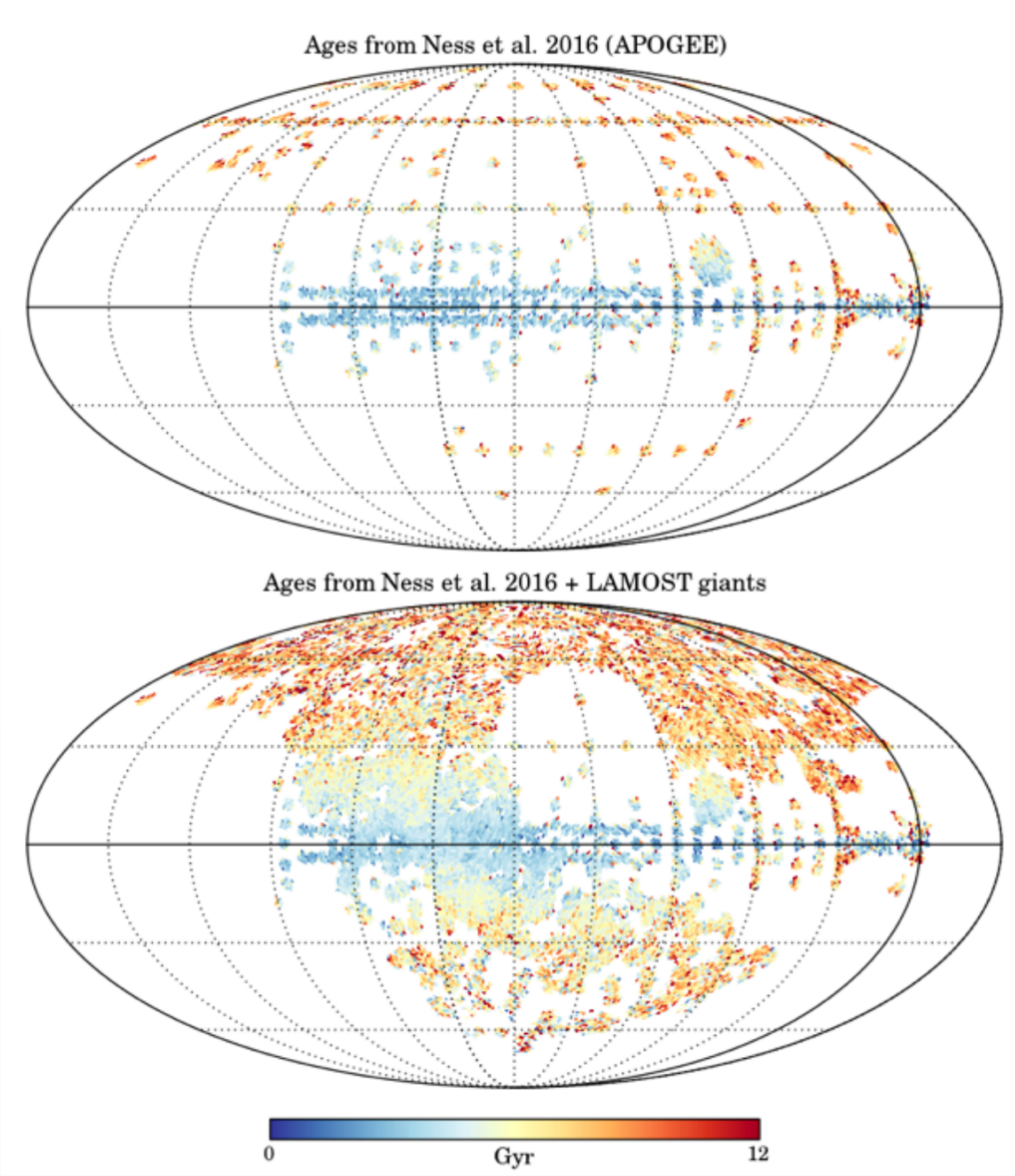
Can put LAMOST stars (R=1800) on APOGEE (R=22,500) parameter and age scale

(Ho et al., 2017a,b)
http://adsabs.harvard.edu/abs/2017ApJ...836....5H
http://adsabs.harvard.edu/abs/2017ApJ...841...40H

Advances with APOGEE — Stellar ages for giants

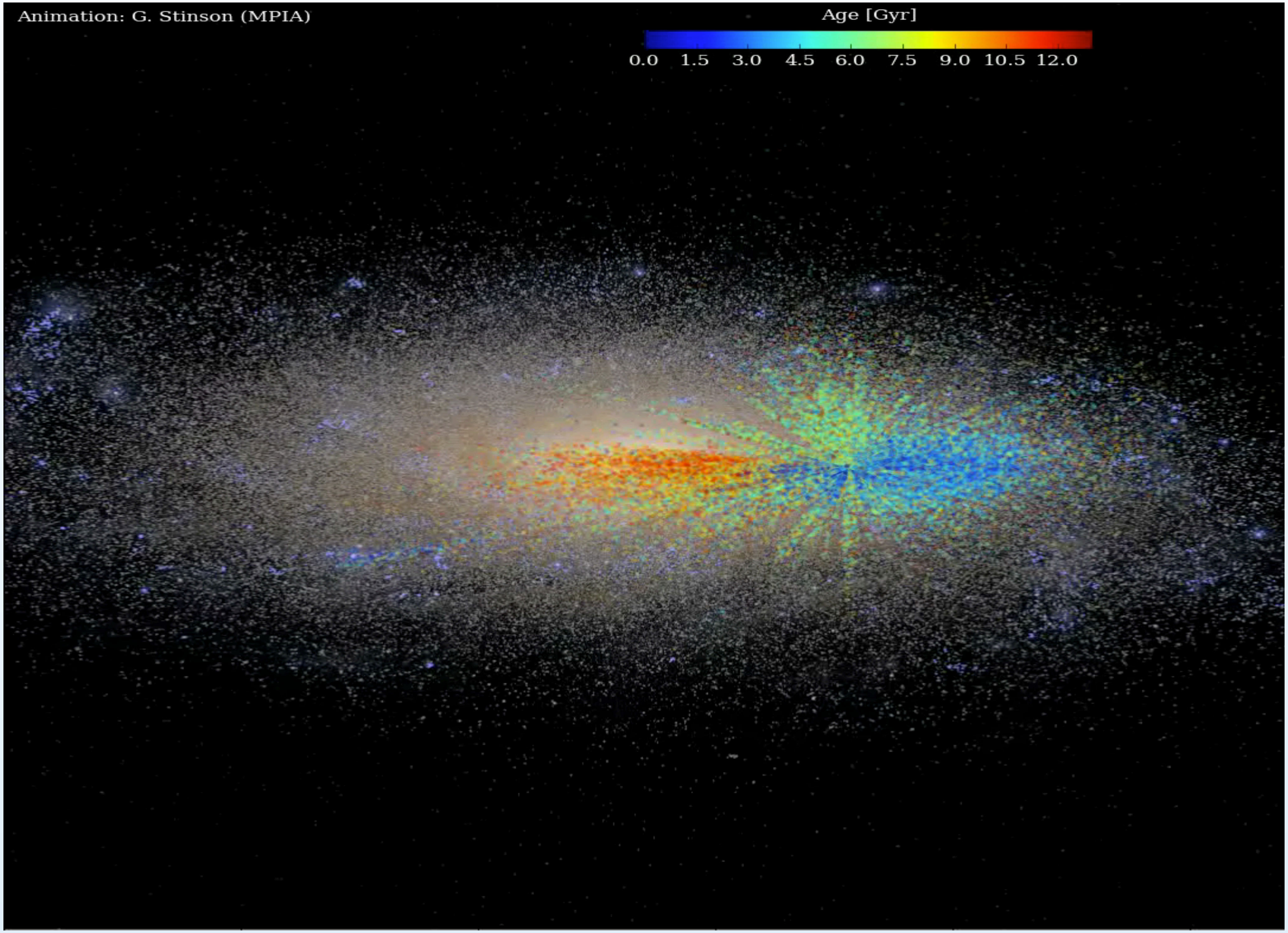
75,000 APOGEE stars

230,000 LAMOST stars



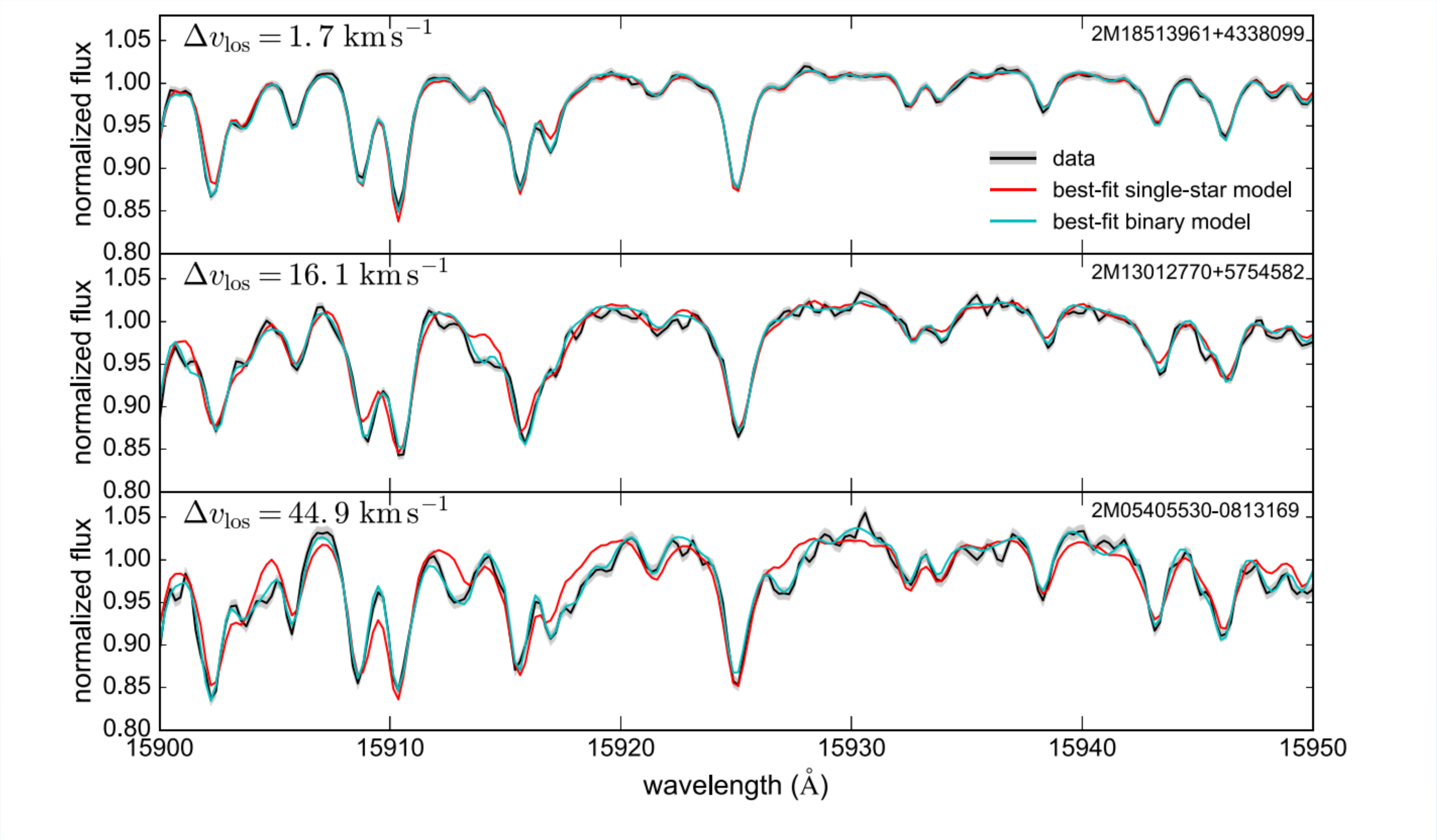
Ho et al. (2017)

Advances with APOGEE — Stellar ages for giants



Advances with APOGEE — data-driven models

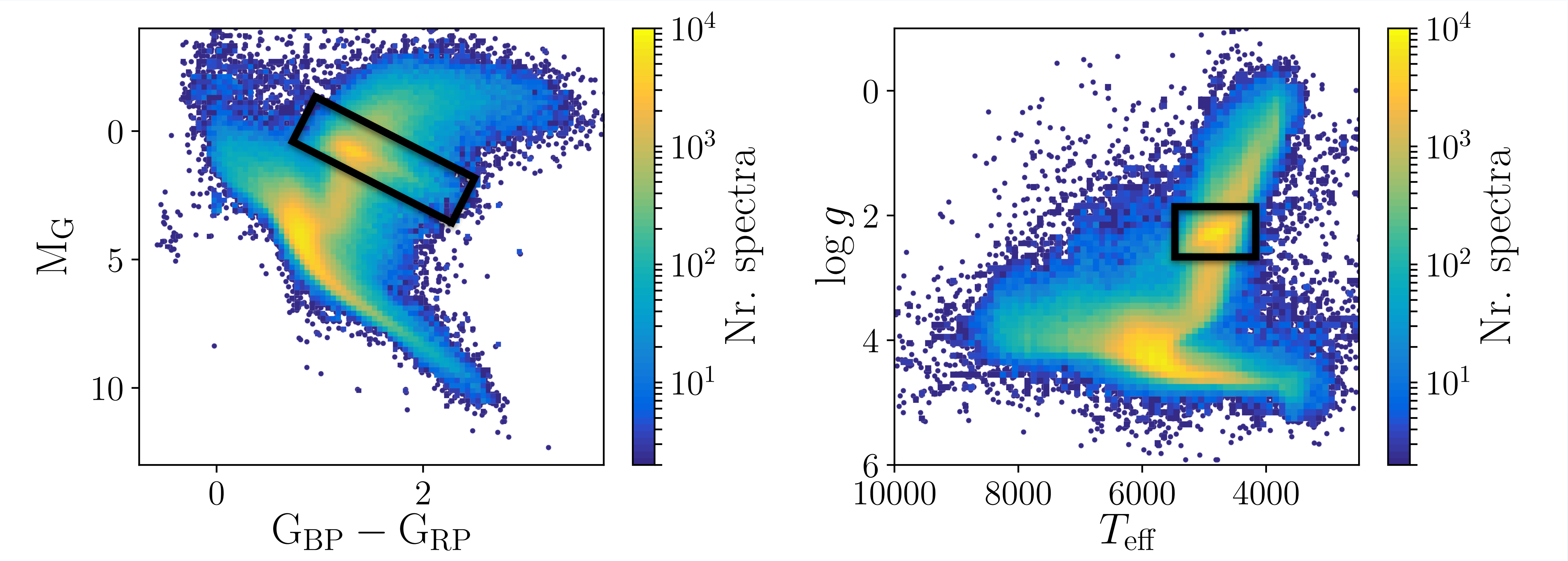
Parameters of binaries + discovery and characterisation of 3000+ main-sequence binaries from APOGEE spectra, El-Badry+ 2018
http://adsabs.harvard.edu/abs/2018MNRAS.476..528E



data-driven modeling of binaries and triples with orbital solutions, understanding stars as families

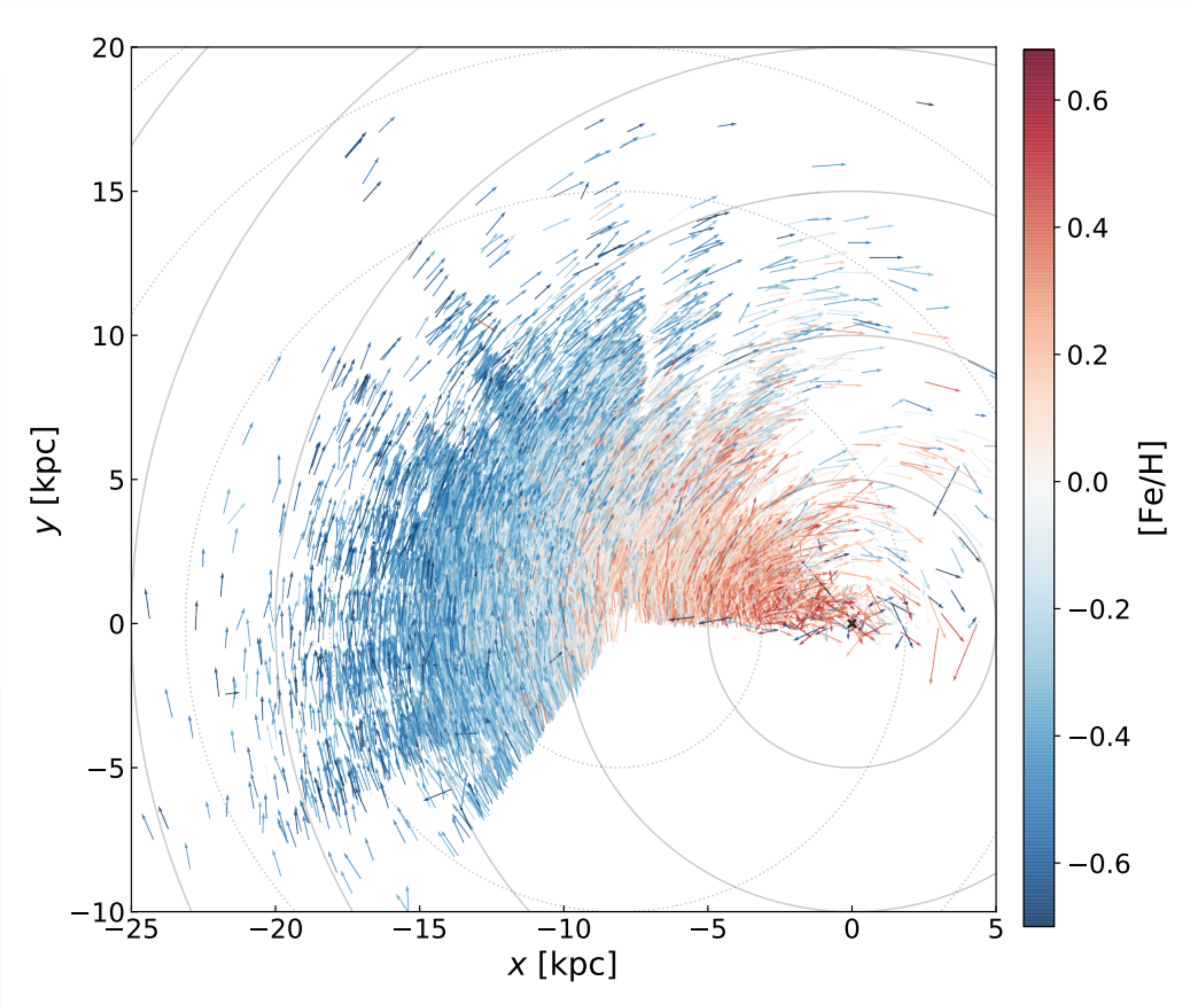
Advances with APOGEE – Distances (complementary to *Gaia*)

The APOGEE Red-clump Catalog: Precise Distances, Velocities, and High-resolution Elemental Abundances over a Large Area of the Milky Way′s Disk – Bovy+ 2014
http://adsabs.harvard.edu/abs/2014ApJ...790..127B



A Large and Pristine Sample of Standard Candles across the Milky Way: 100,000 Red Clump Stars with 3% Contamination - Ting+ 2018
http://adsabs.harvard.edu/abs/2018ApJ...858L...7T

Advances with APOGEE – Distances (complementary to *Gaia*)



Eilers+2019
http://adsabs.harvard.edu/abs/2019ApJ...871..120E

Data-driven modeling using APOGEE spectra and Gaia photometry – **spectrophotometric distances precise to 10 %**

also Leung & Bovy, 2019
http://adsabs.harvard.edu/abs/2019MNRAS.483.3255L

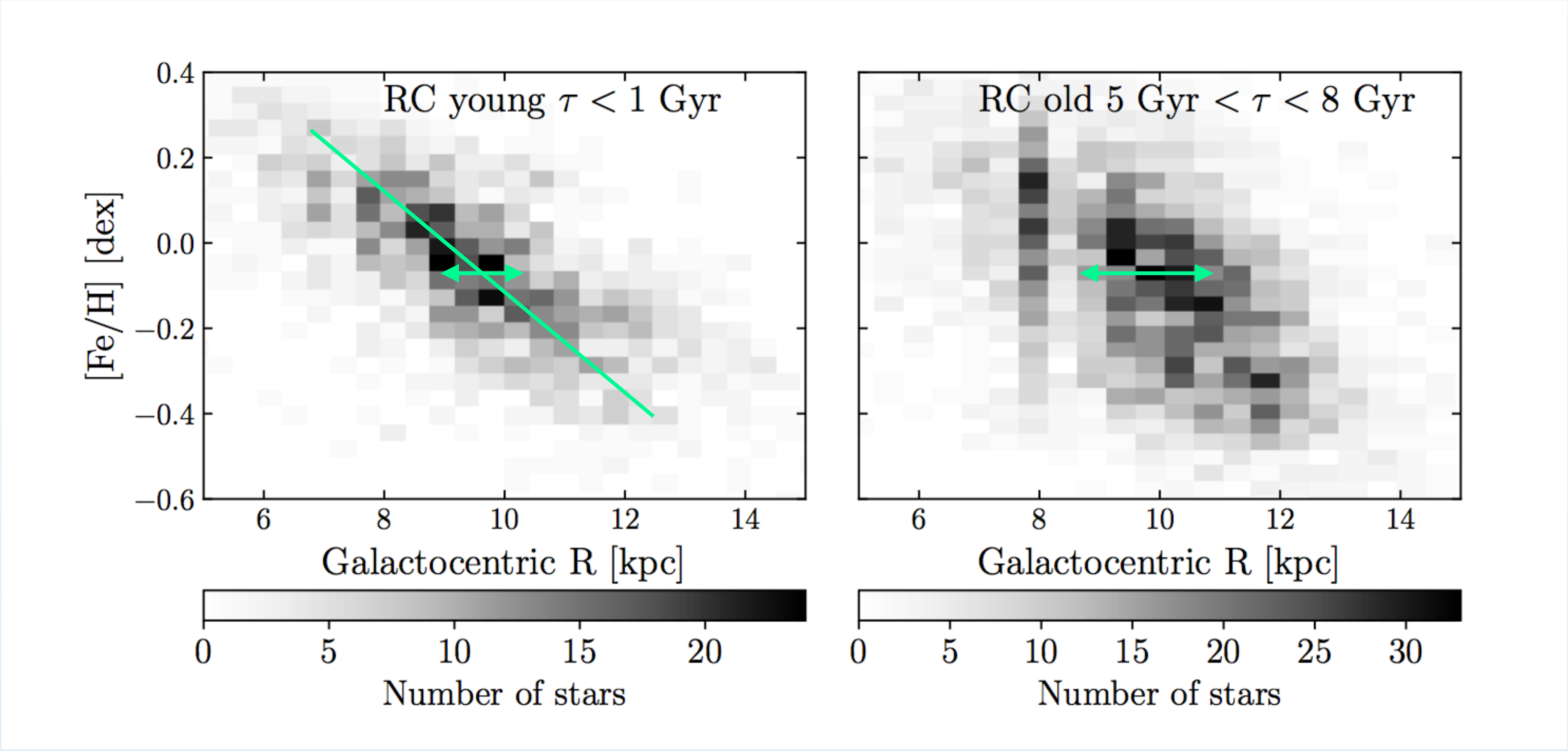
and Bovy+2019
https://adsabs.harvard.edu/abs/2019arXiv190511404B

Suddenly we can get precision orbits for millions of stars far away!

How far do stars move from their birthplaces over time?

Measuring Radial Orbit Migration in the Galactic Disk, Frankel+ 2018
http://adsabs.harvard.edu/abs/2018ApJ...865...96F

- Sample of 20,000 APOGEE red clump stars with [Fe/H], ages, R_{GAL}
  - Radial migration: later times stars are more distributed



Sven Buder (MPIA)

Advances with APOGEE data – feasibility of chemical tagging

Blind chemical tagging with DBSCAN: prospects for spectroscopic surveys

- construct a realistic set of synthetic clusters, creating both observed spectra and derived chemical abundances for each star
- predict recovering over 600 clusters with at least 10 observed members and 70% membership homogeneity in a sample similar to the APOGEE survey

Price-Jones & Bovy 2019 http://adsabs.harvard.edu/doi/10.1093/mnras/stz1260

but see Ness et al., 2018 for far more pessimistic view
Galactic Doppelgängers: The Chemical Similarity Among Field Stars and Among Stars with a Common Birth Origin
http://adsabs.harvard.edu/abs/2018ApJ...853..198N

GALAH

Galactic Archaeology with HERMES

Setup

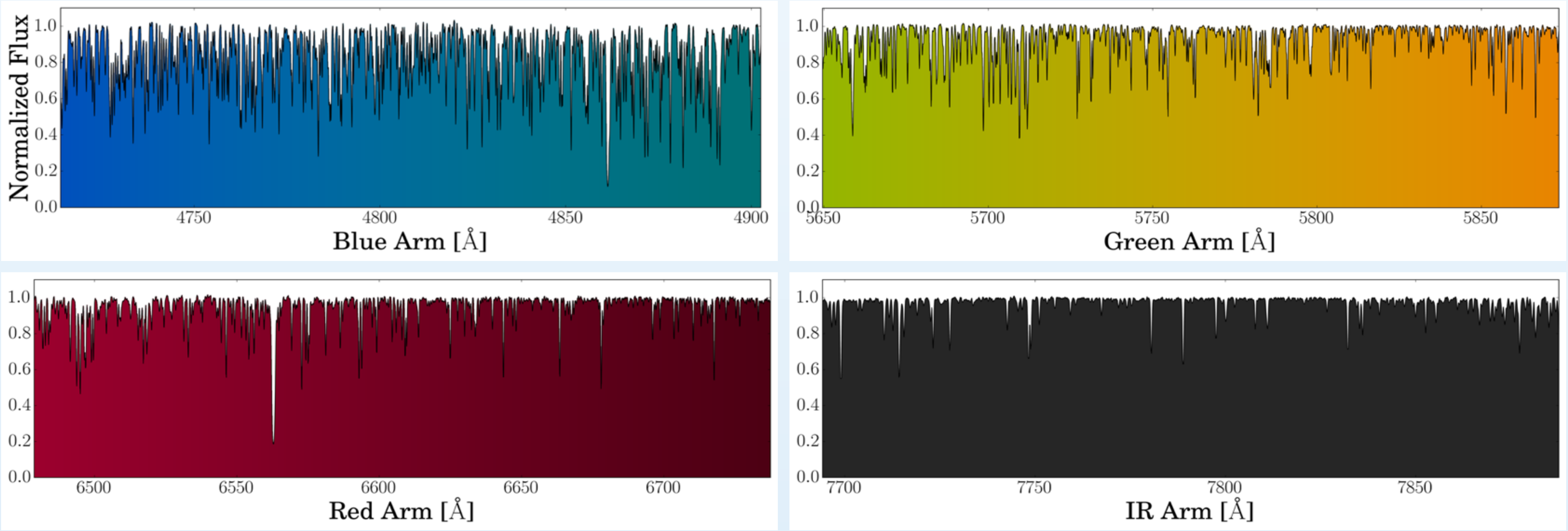
4700-7900 Å (4 HERMES-arms, 400 fibers),
R 27,000, Teff, logg, [M/H], and 30 abundances

MW

thin disk (76%), thick disk (22%),
stellar halo, and bulge

Aim

Chemical tagging experiment



GALAH

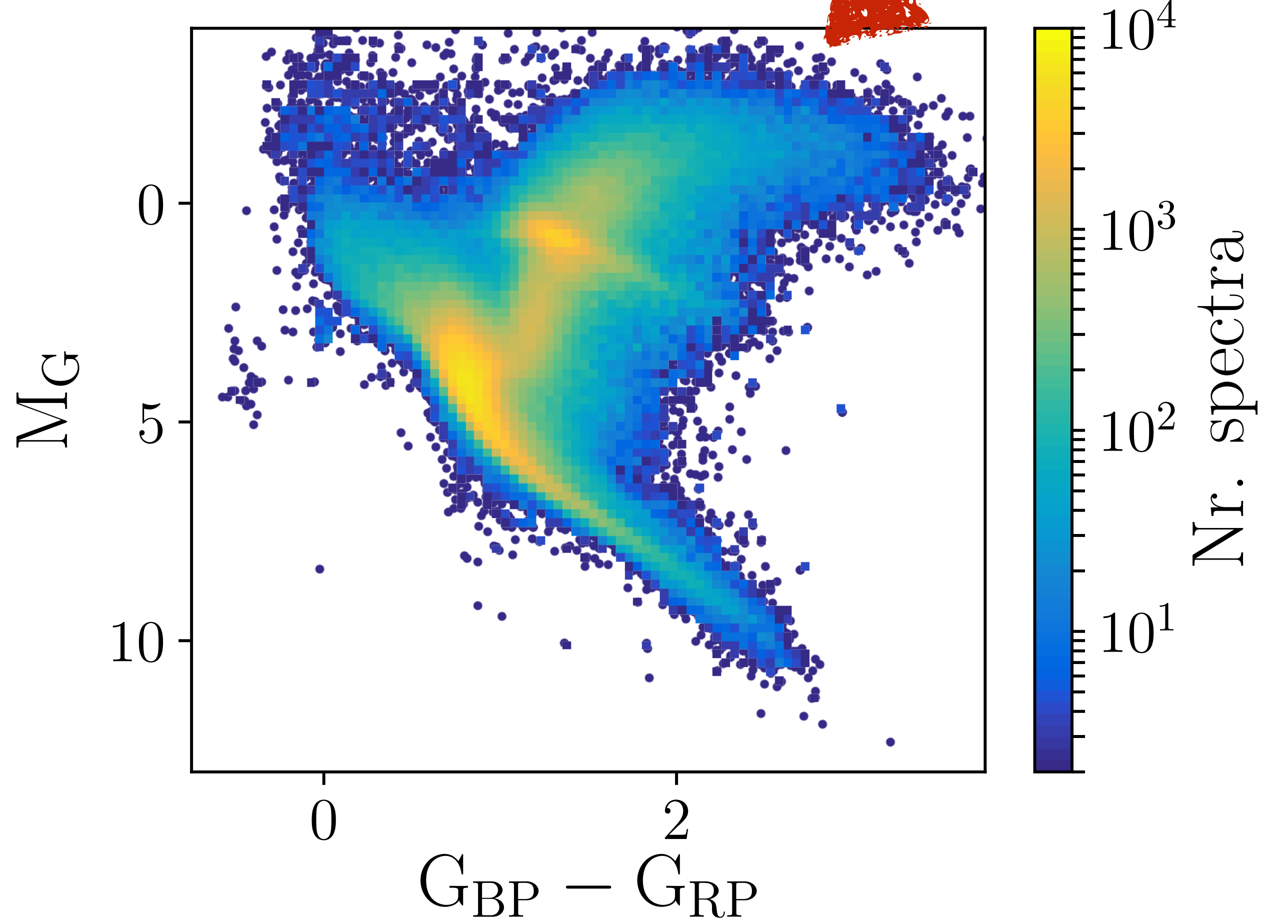
- Public data release of parameters and abundances for 350,000 stars (650,000 coming at the beginning of 2020)

wget --no-check-certificate https://datacentral.aao.gov.au/teamdata/GALAH/public/GALAH_DR2.1_catalog.fits

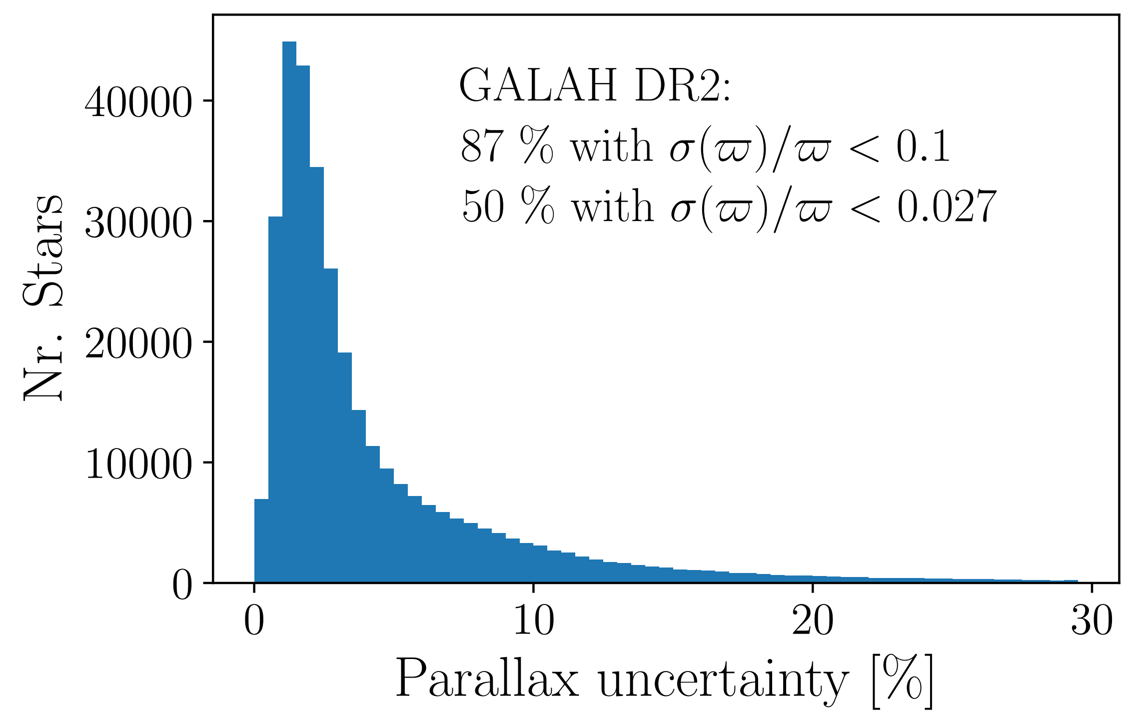
- Single visits to stars
- Many more elements than APOGEE from more families (Li, Ba, Eu)
- Unlike APOGEE most stars are dwarfs
- Data release paper - Buder+2018: http://adsabs.harvard.edu/abs/2018MNRAS.478.4513B

GALAH: At the sweet spot of Gaia

Gaia



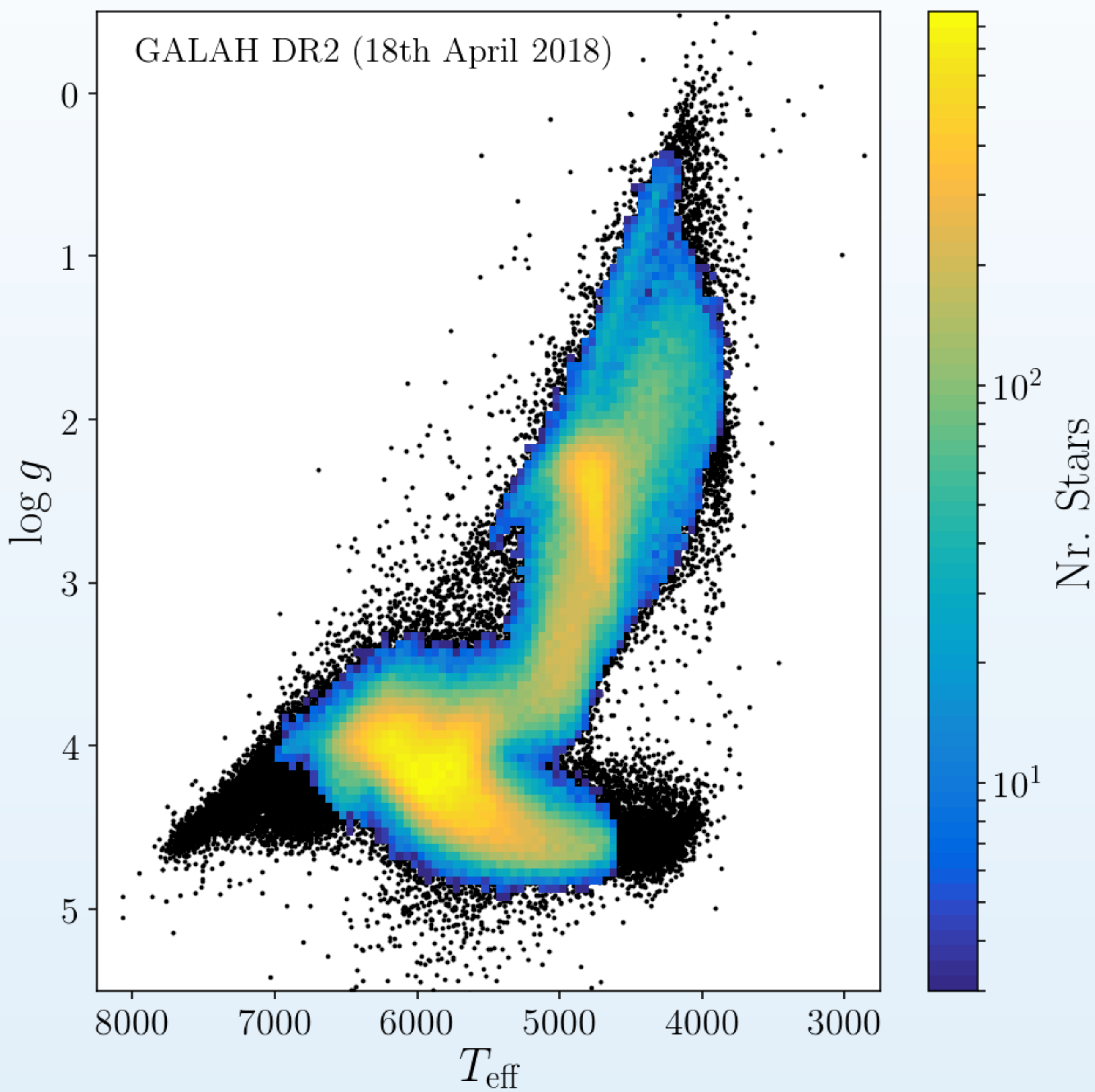
GALAH

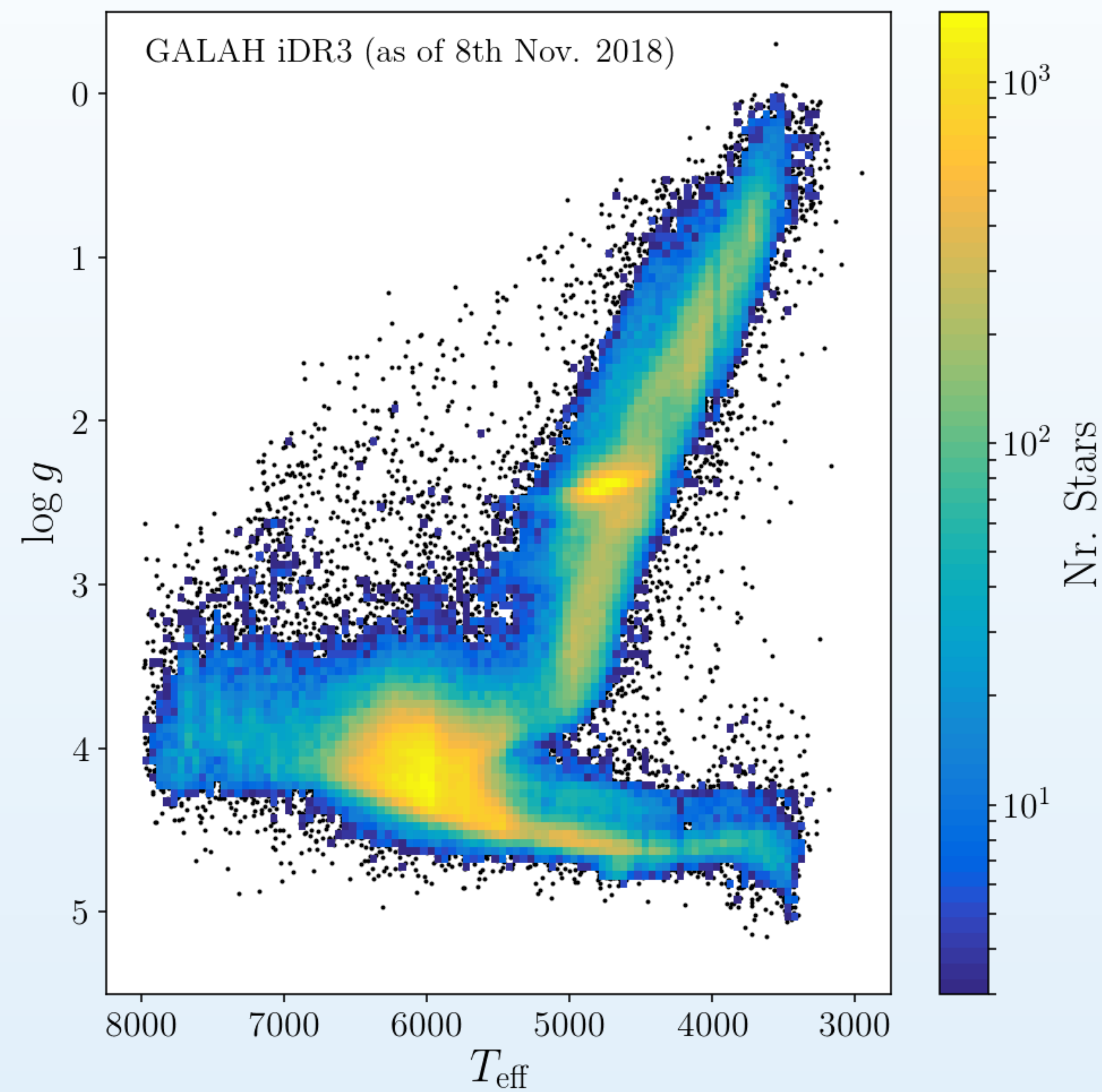


$$\log\left(\frac{L_{\mathrm{bol}}}{L_{\mathrm{bol},\odot}}\right) = 0.4 \cdot (M_{\mathrm{bol},\odot} - M_{\mathrm{bol}}) + \frac{L_{\mathrm{bol}}}{L_{\mathrm{bol},\odot}} = \left(\frac{\mathcal{R}}{\mathcal{R}_\odot}\right)^2 \cdot \left(\frac{T_{\mathrm{eff}}}{T_{\mathrm{eff},\odot}}\right)^4$$

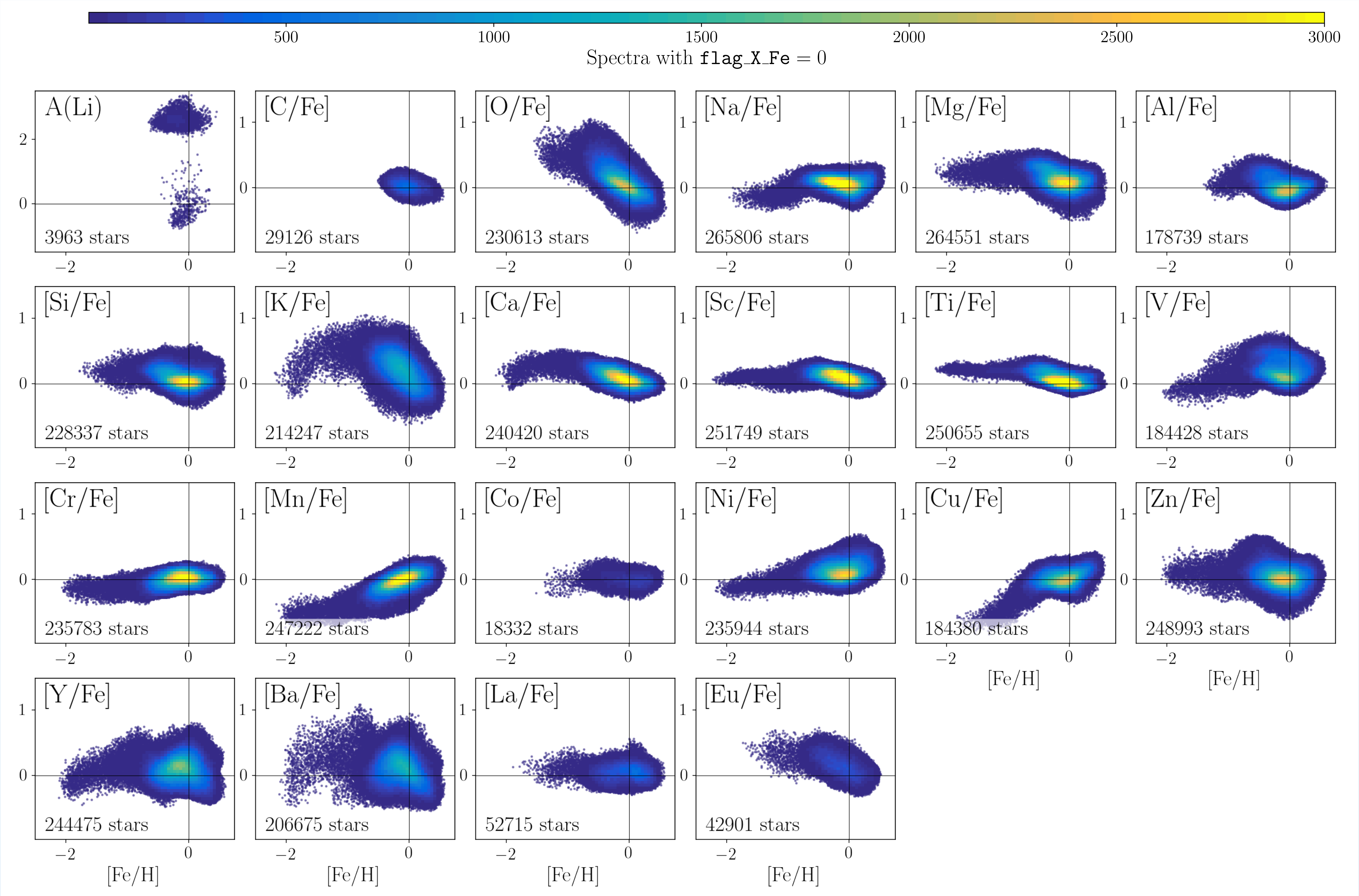
Sven Buder (MPIA)

GALAH: At the sweet spot of Gaia





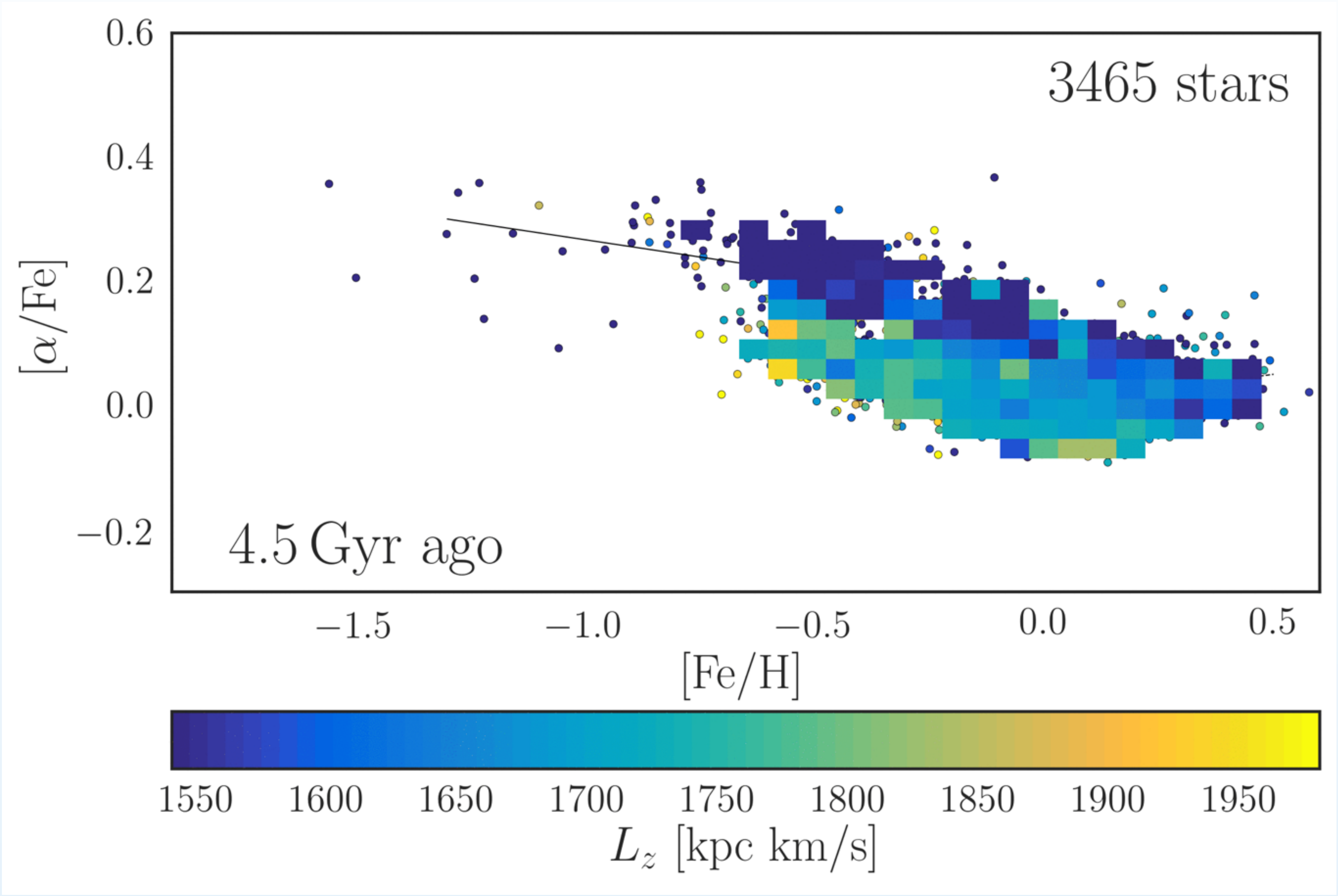
New advances with GALAH — a lot of abundances



Buder et al. (2018)

Sven Buder (MPIA)

New advances with GALAH — temporal chemistry



Buder+2019

http://adsabs.harvard.edu/abs/2019A%26A...624A..19B

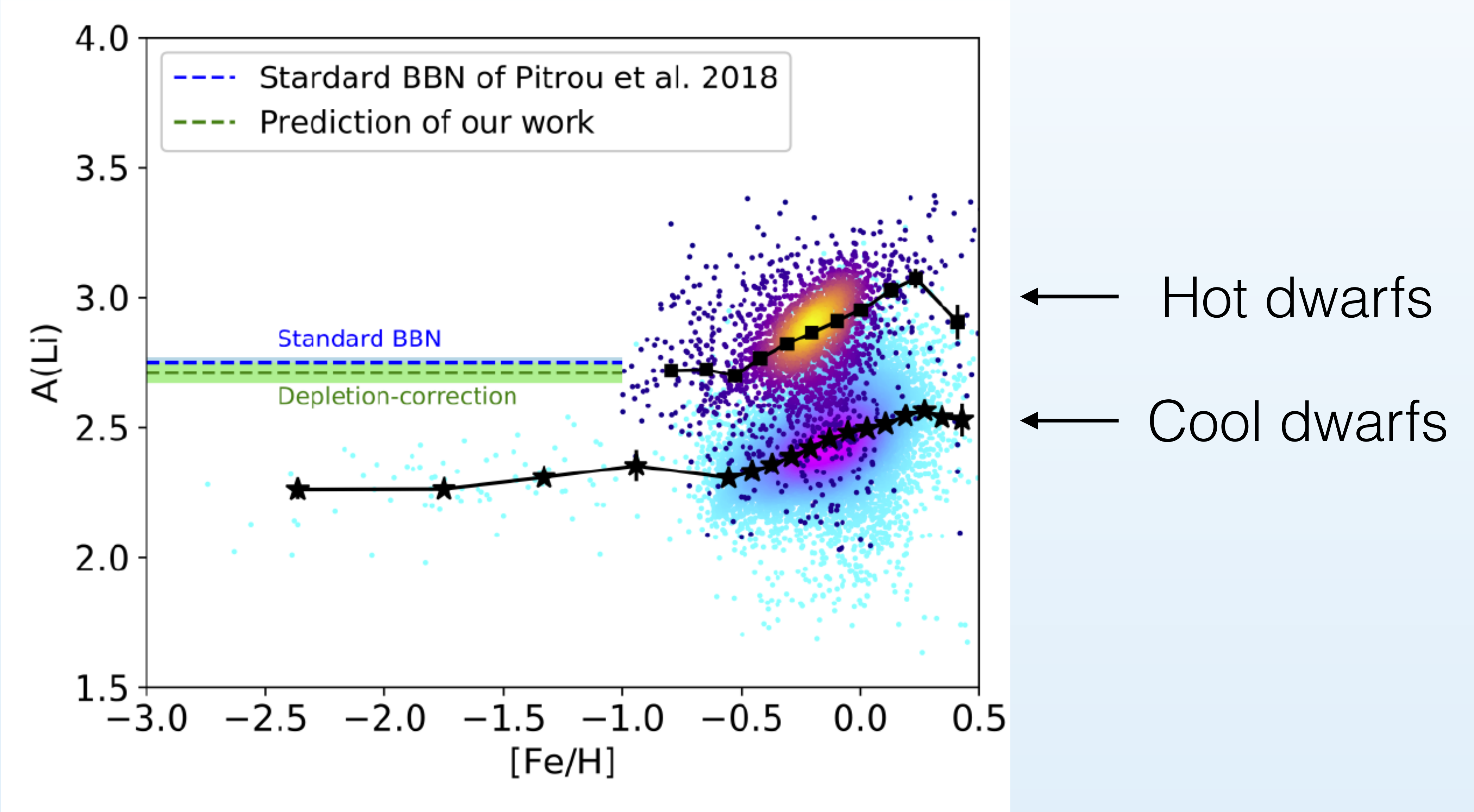
This was just a pilot study with GALAH+TGAS
Now we can repeat this exercise with 400k+ stars!

Sven Buder (MPIA)

Advances with GALAH — Lithium

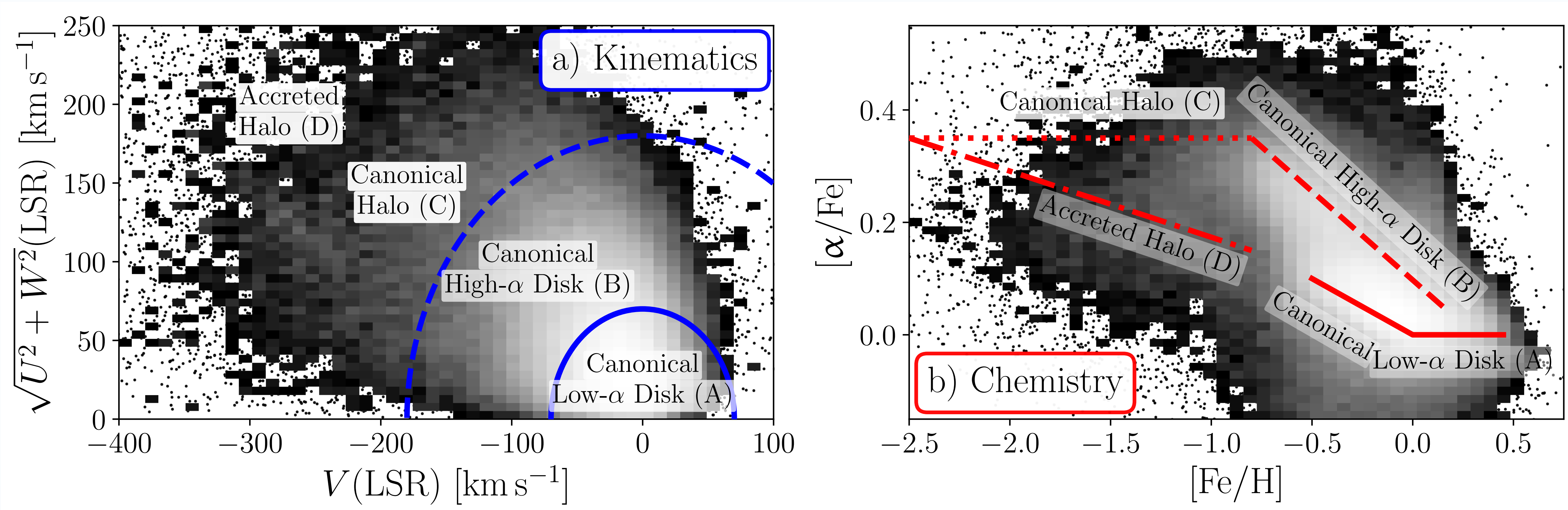
"Missing" Lithium in metal-poor stars?

Big Bang Nucleosynthesis prediction: A(Li) ~ 2.75
Measurements in old, metal-poor, cool dwarfs: A(Li) ~ 2.20

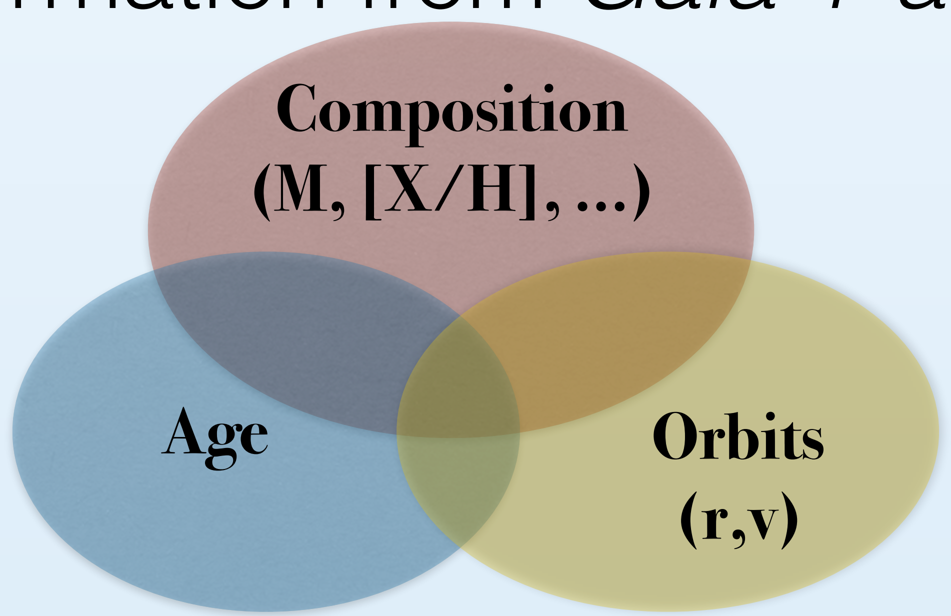


Gao et al. (in prep.)

Advances with GALAH data – chemodynamics + ages



Remember: A large fraction of GALAH stars have very good 5D information from *Gaia + are turnoff stars*

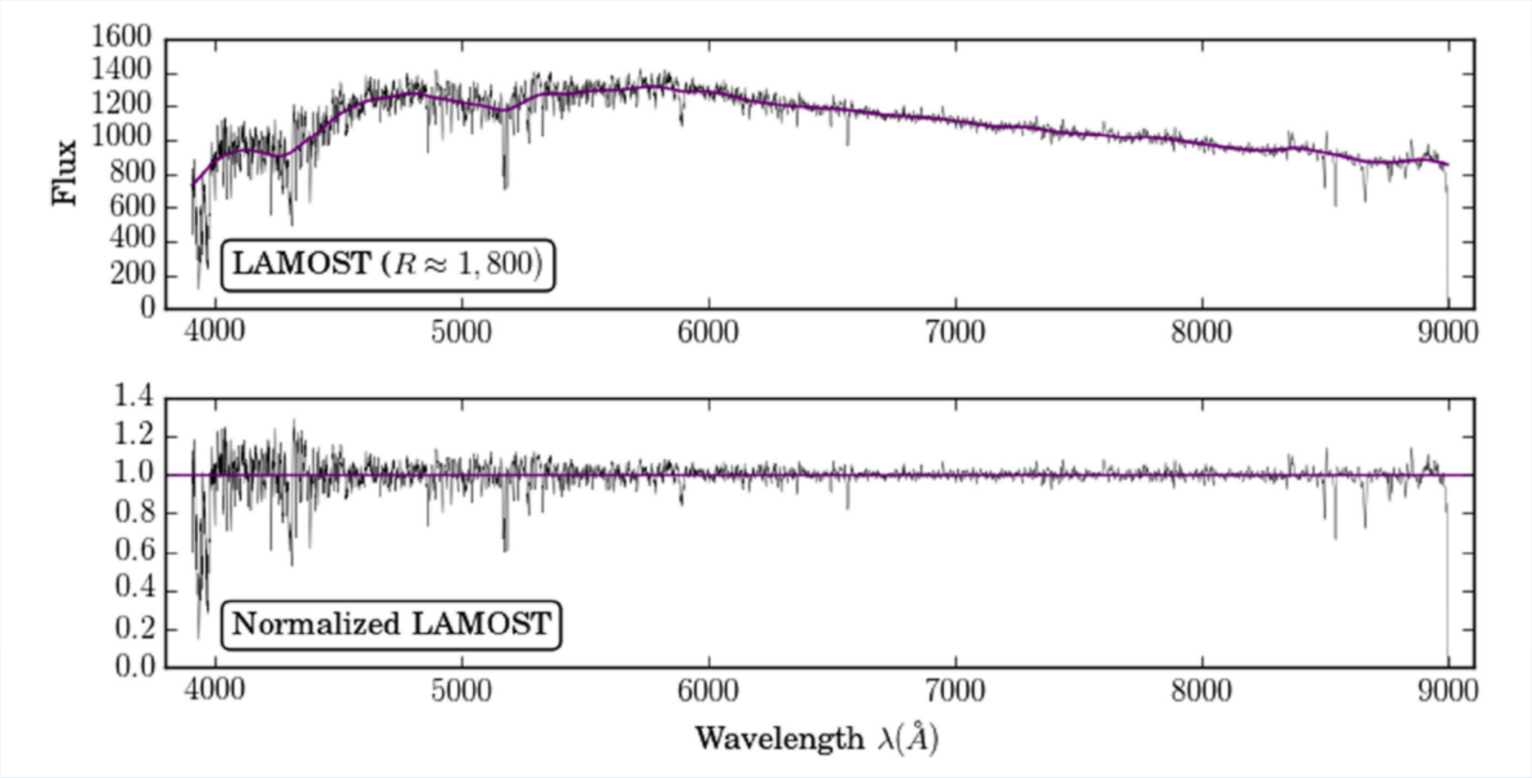


Sven Buder (MPIA)

LAMOST

Large Sky Area Multi-Object Fiber Spectroscopic Telescope

Setup	3700-9000 Å with 4000 fibers, R 1800
MW	halo and disk with LAMOST Experiment for Galactic Understanding & Exploration (LEGUE)
Aim	Galactic structure, formation history, kinematical and dynamical evolution + LAMOST ExtraGAlactic Survey (LEGAS)

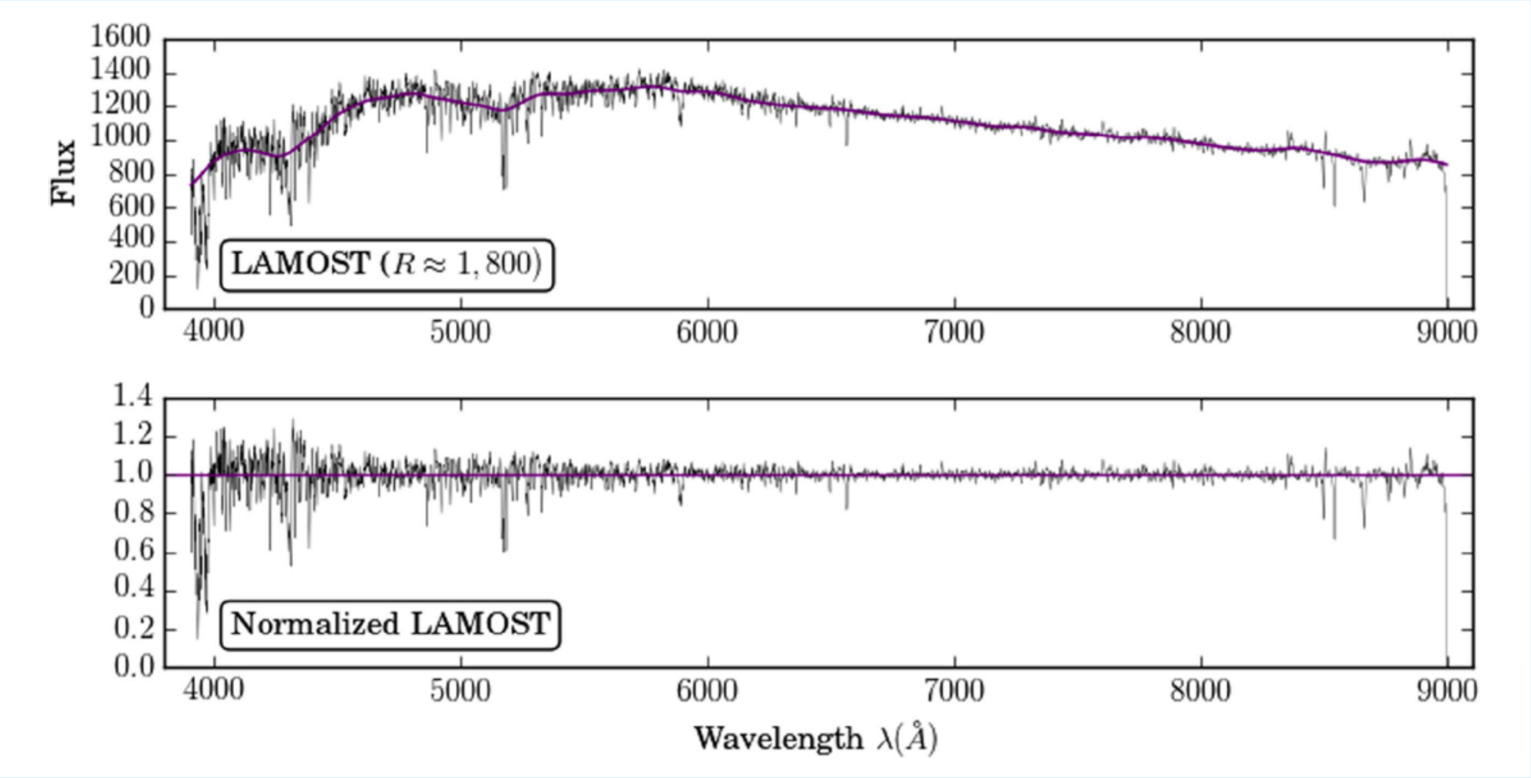


LAMOST

- Public data release of parameters and spectra for 7 million stars

http://dr4.lamost.org/catalogue (ask Adam Wheeler how to get the spectra)

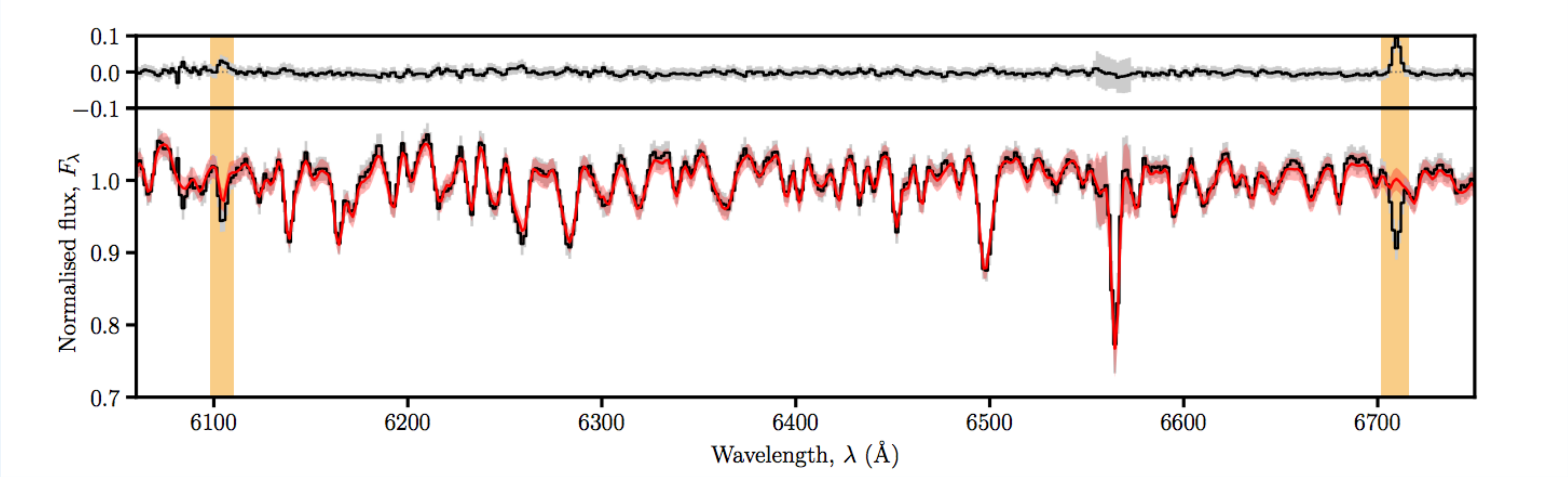
- Overlap between LAMOST-> APOGEE = stellar ages for LAMOST
- Overlap between LAMOST -> GALAH = neutron capture abundances for LAMOST, Lithium abundances for LAMOST



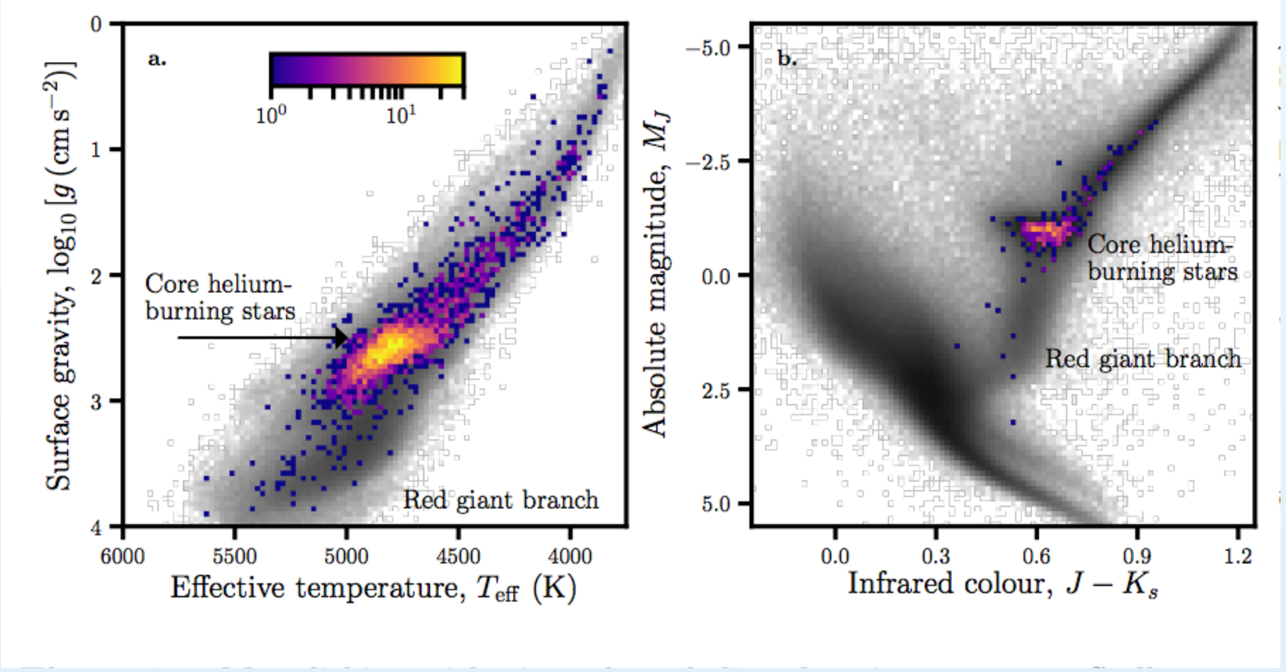
Sven Buder (MPIA)

LAMOST: low resolution spectra are rich in information

Ho et al., 2017 - derivation of C/Fe and N/Fe, can get many more [X/Fe]

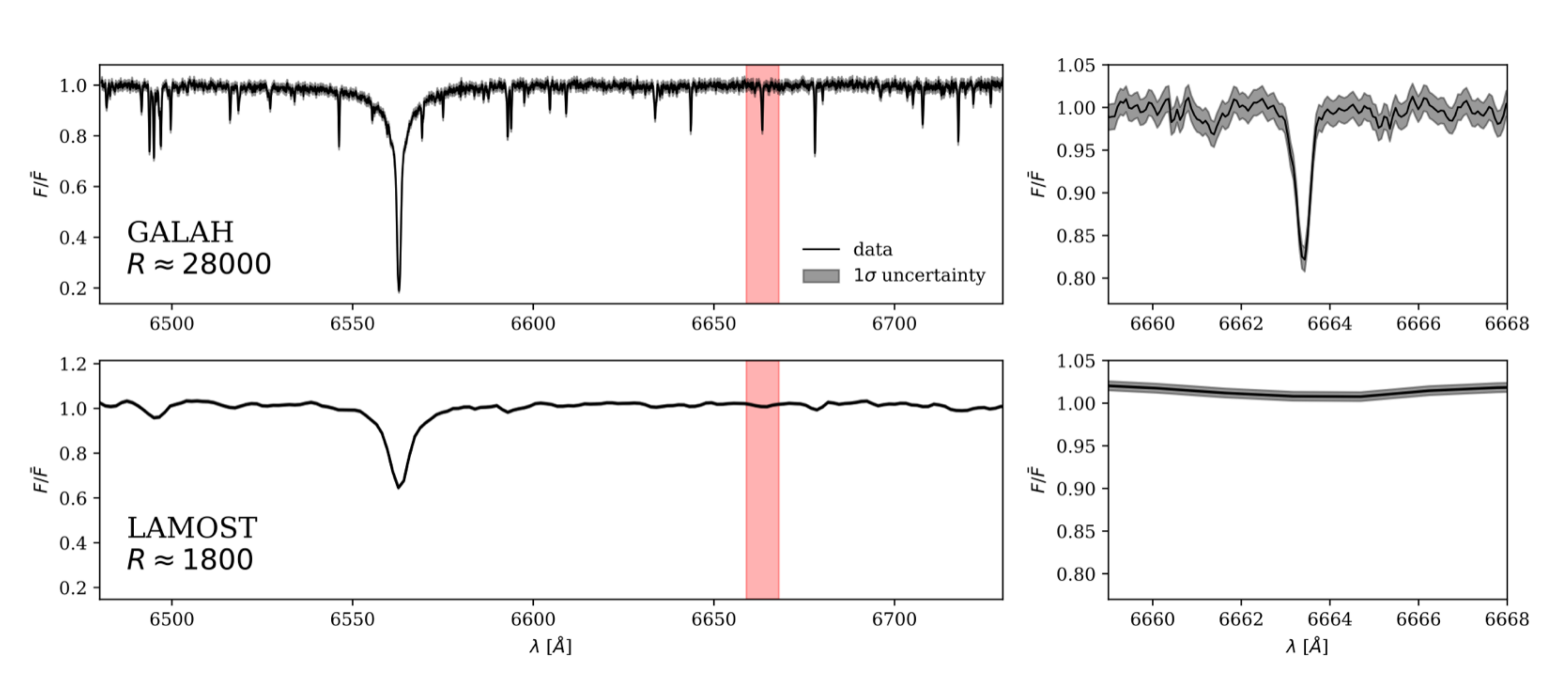


Empirical model from Ho et al., 2017a,b (Teff, logg, [Fe/H], [α/Fe], C,N, but no Li!)



- 2000 Lithium rich stars in the disk (Casey+ 2019) https://arxiv.org/pdf/1902.04102.pdf
- Scenarios: Li enhancement from tidal interaction **binaries** & planet engulfment

LAMOST: low resolution spectra are rich in information

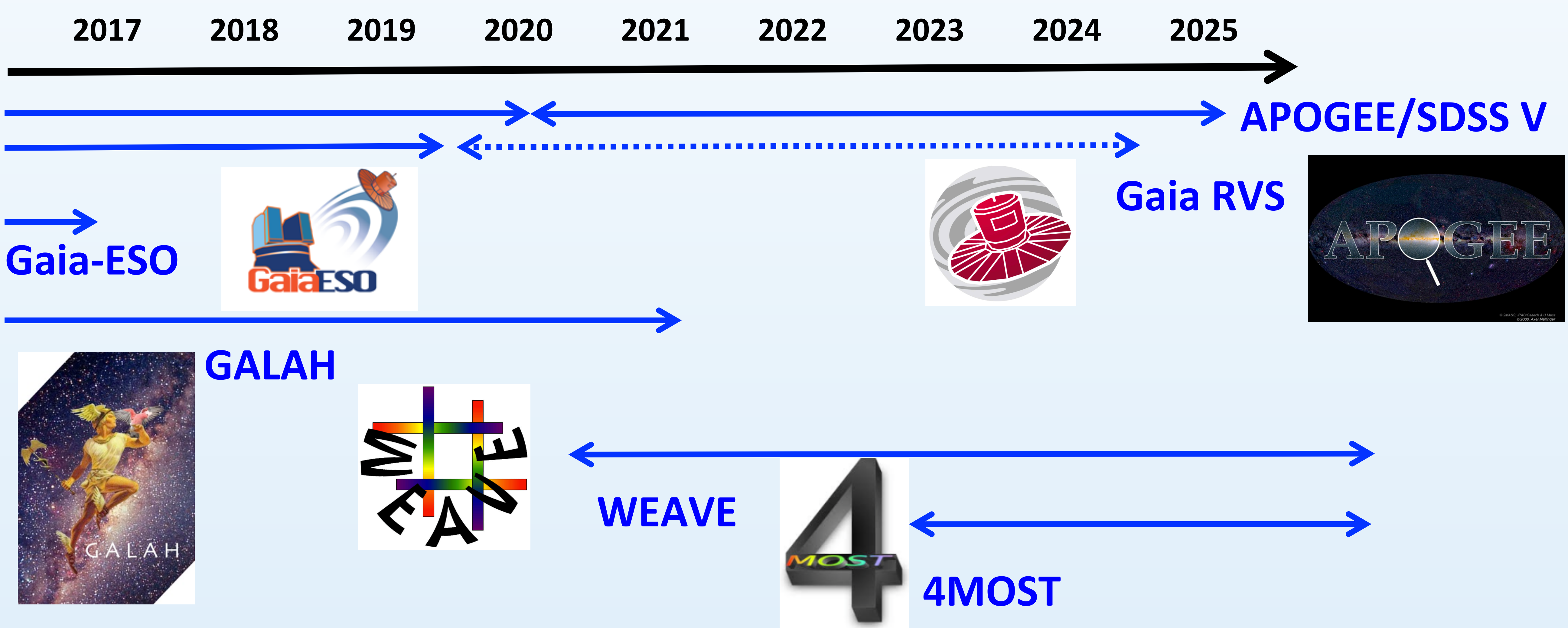


Wheeler et al., in prep

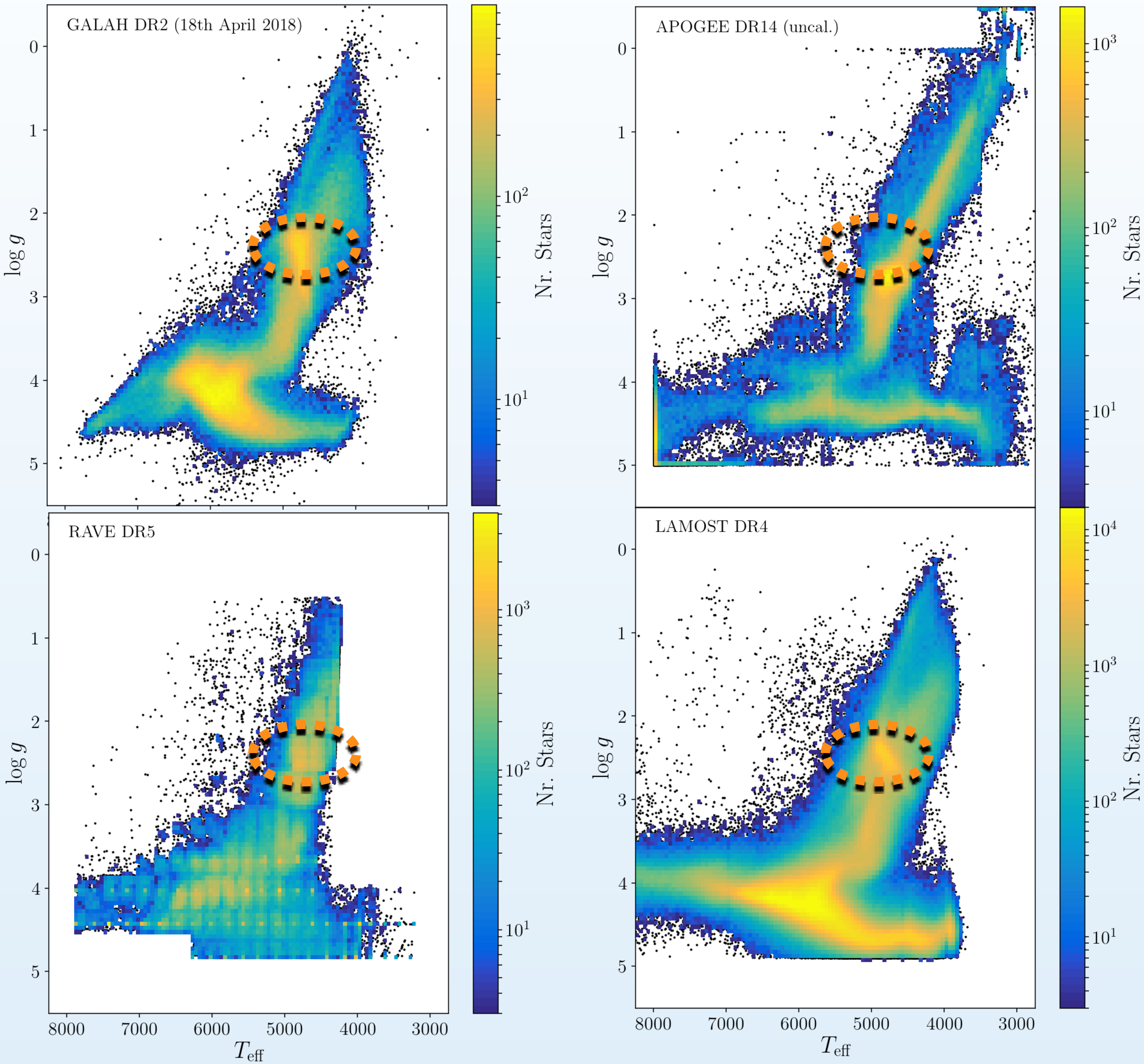
Measuring Oxygen Abundances from Stellar Spectra without Oxygen Lines, Ting+ 2018, http://adsabs.harvard.edu/abs/2018ApJ...860..159T

What's next?

- We have millions of spectra, nearby, toward the bulge, in the disk, some in the halo
- Yet we are missing the MAP



We need to improve our accuracy!



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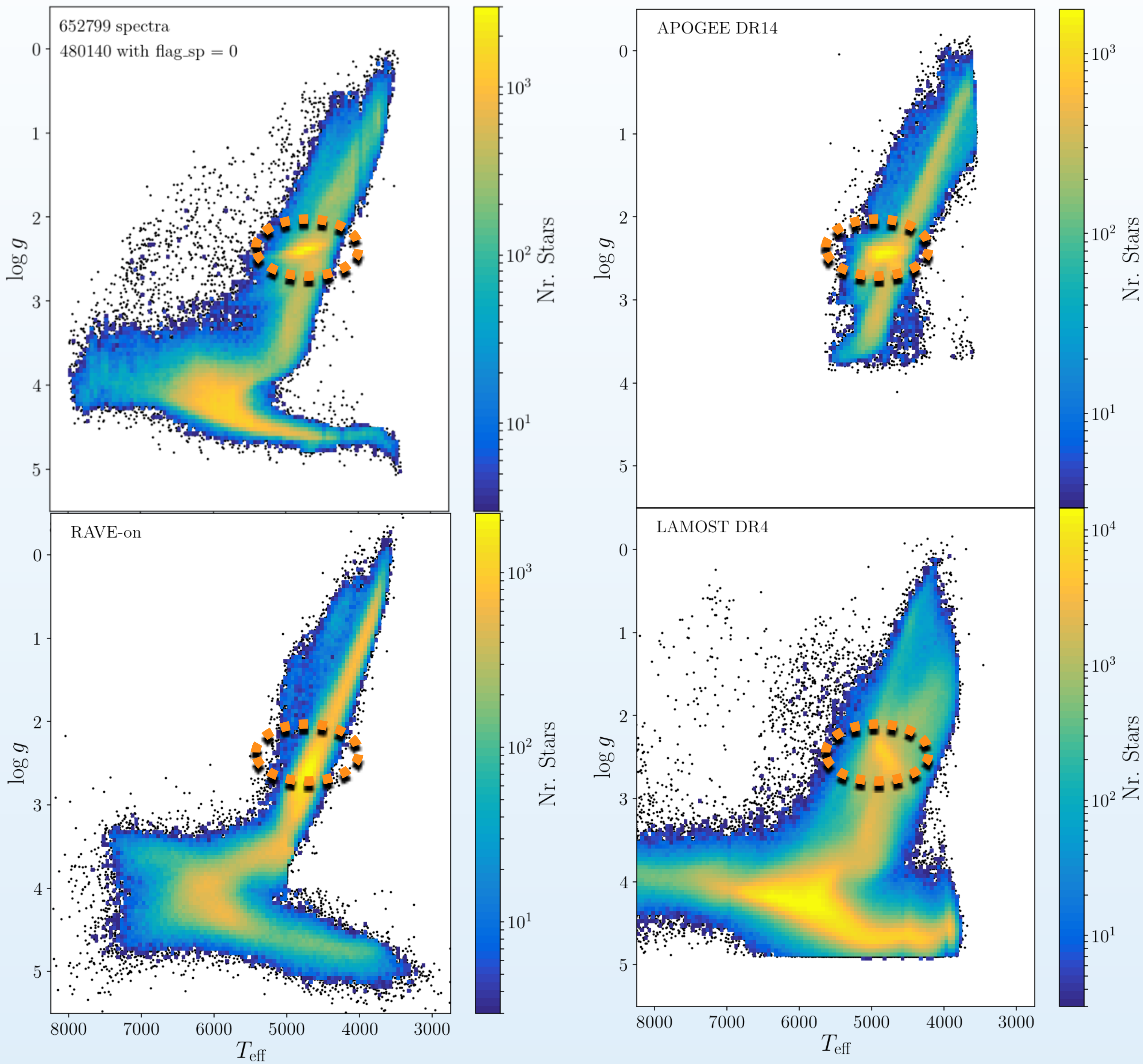
We need to improve our accuracy!



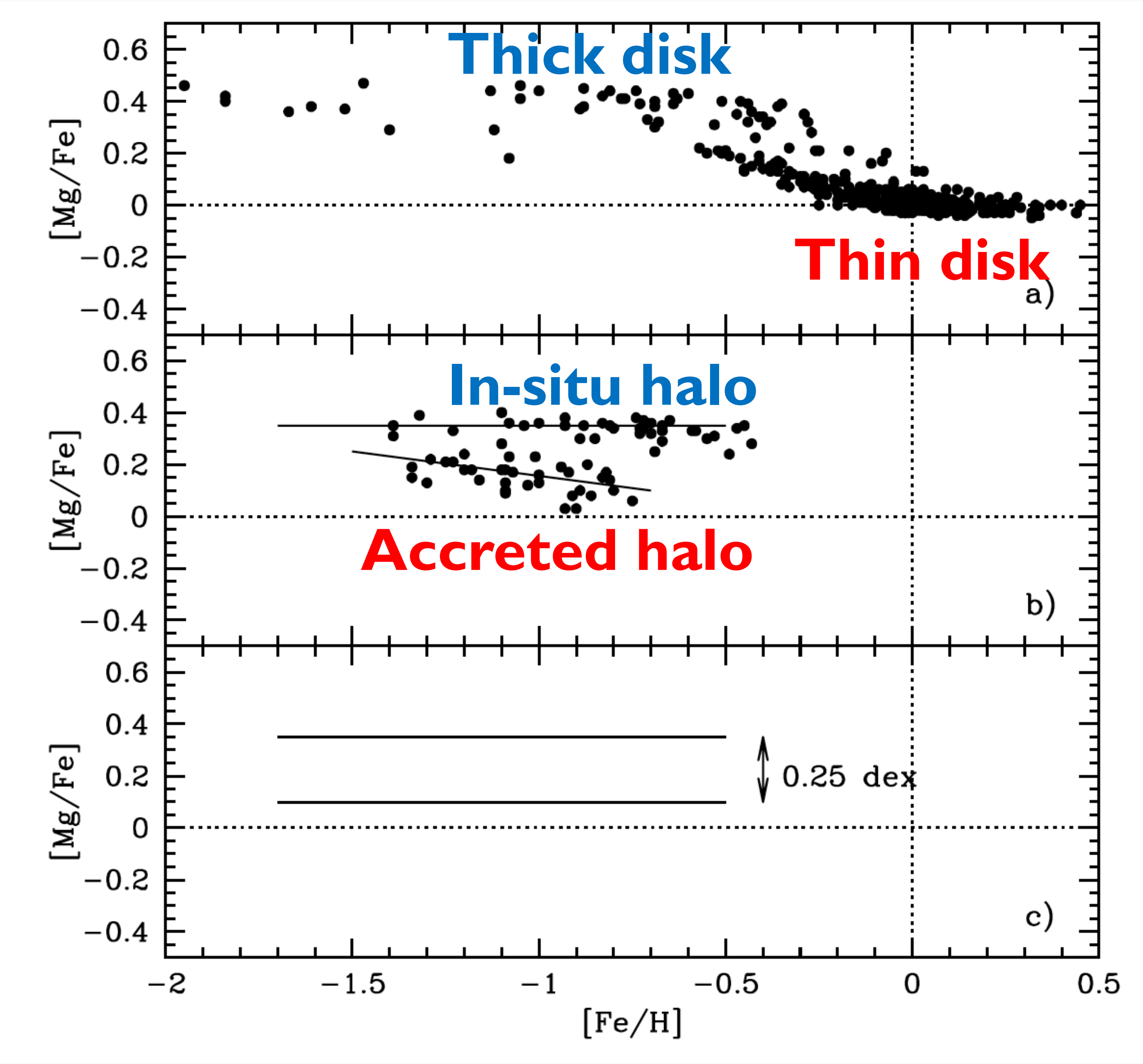
External information

Global calibration

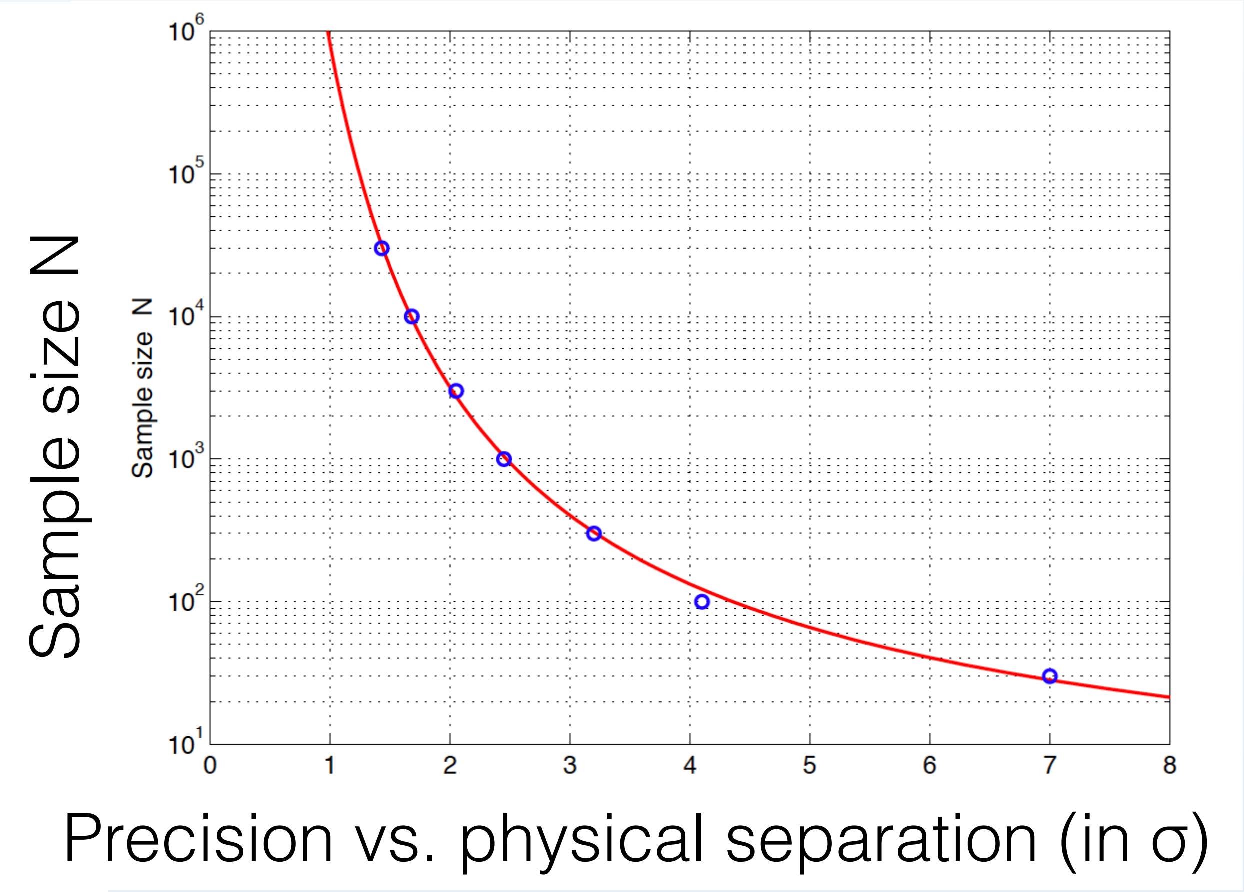
Survey overlap

Sven Buder (MPIA)

We need to improve our precision!



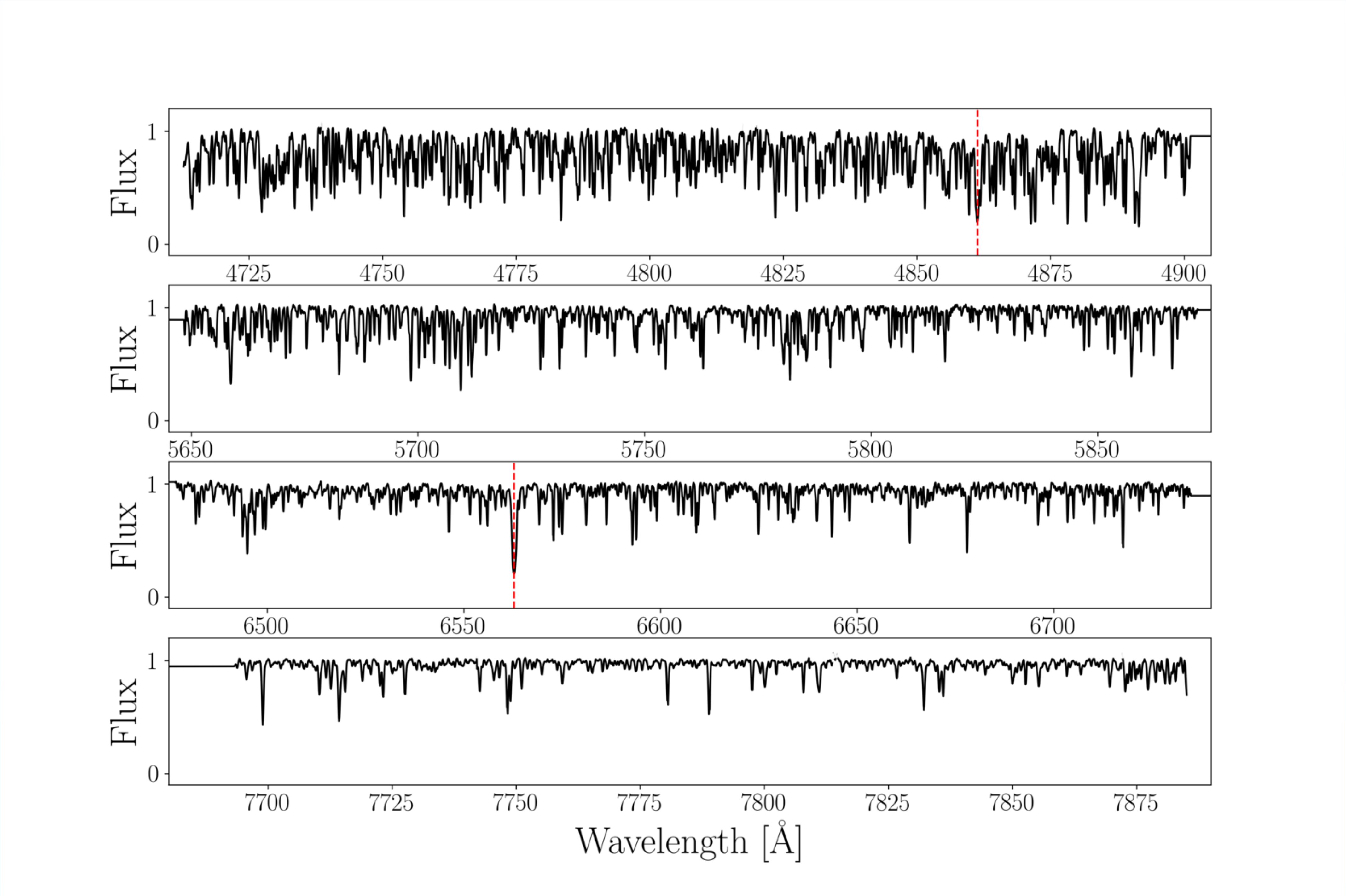
The sample size needed to separate 2 Gaussian populations grows exponentially with decreasing separation in units of σ (abundance precision)



Lindegren & Feltzing (2013)
http://adsabs.harvard.edu/abs/2013A%26A...553A..94L

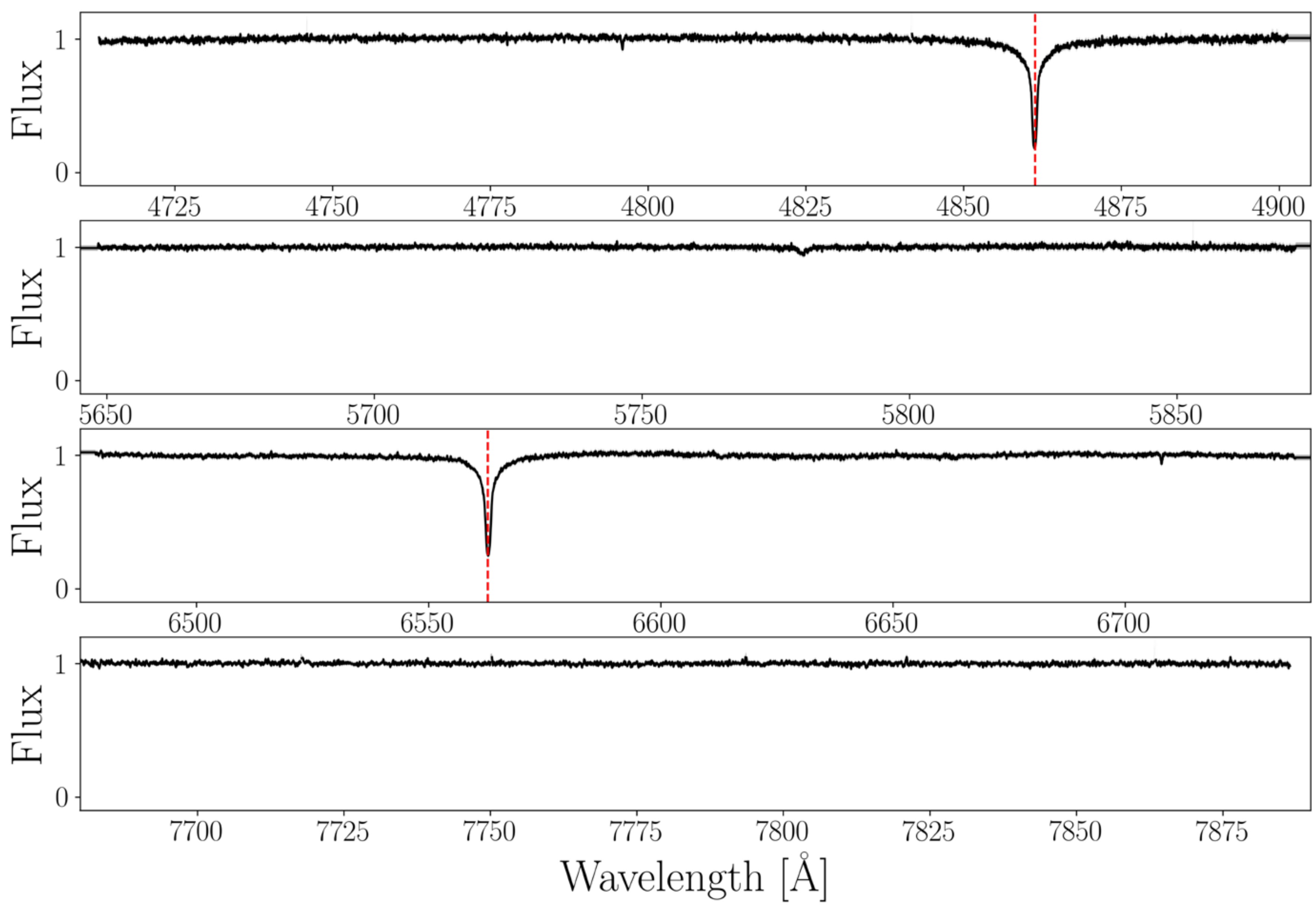
Sven Buder (MPIA)

Climbing down the metallicity ladder



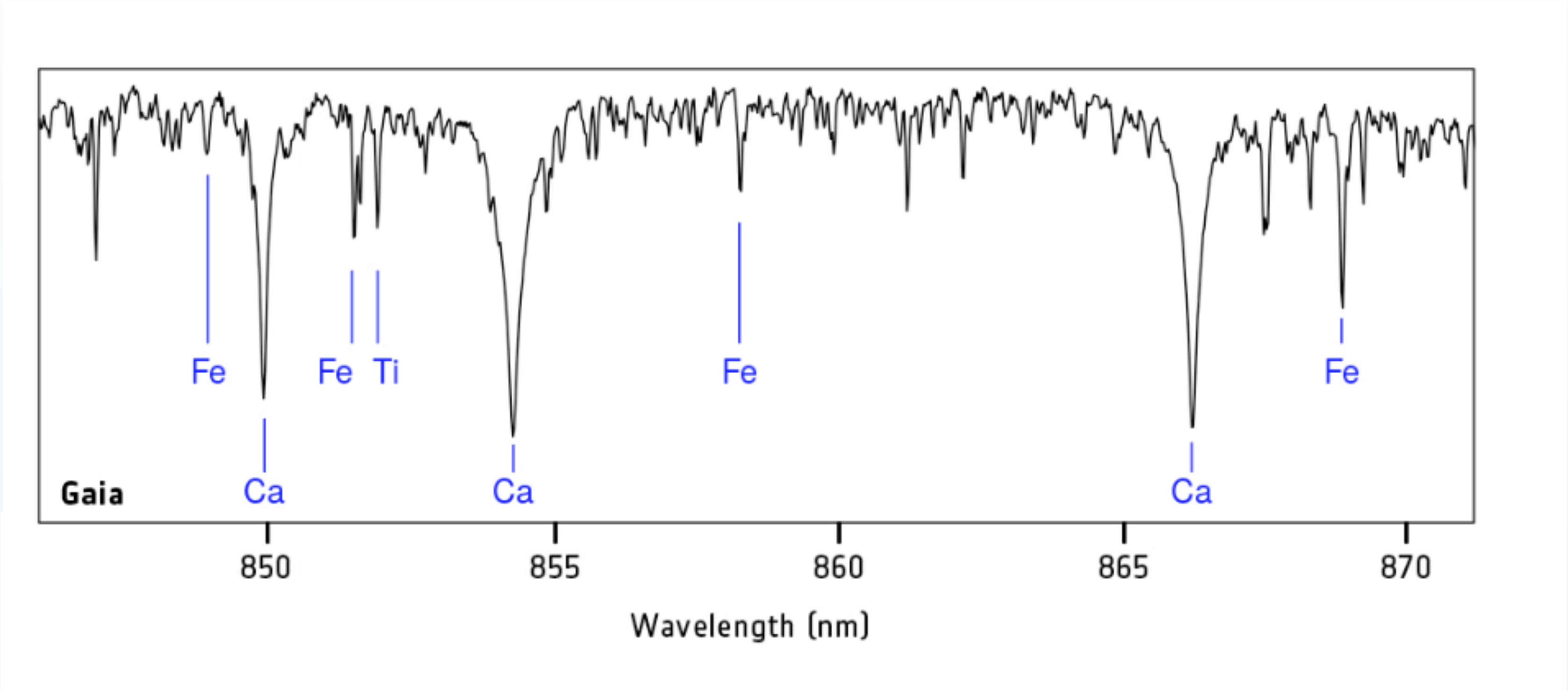
[Fe/H] ~ 0.4

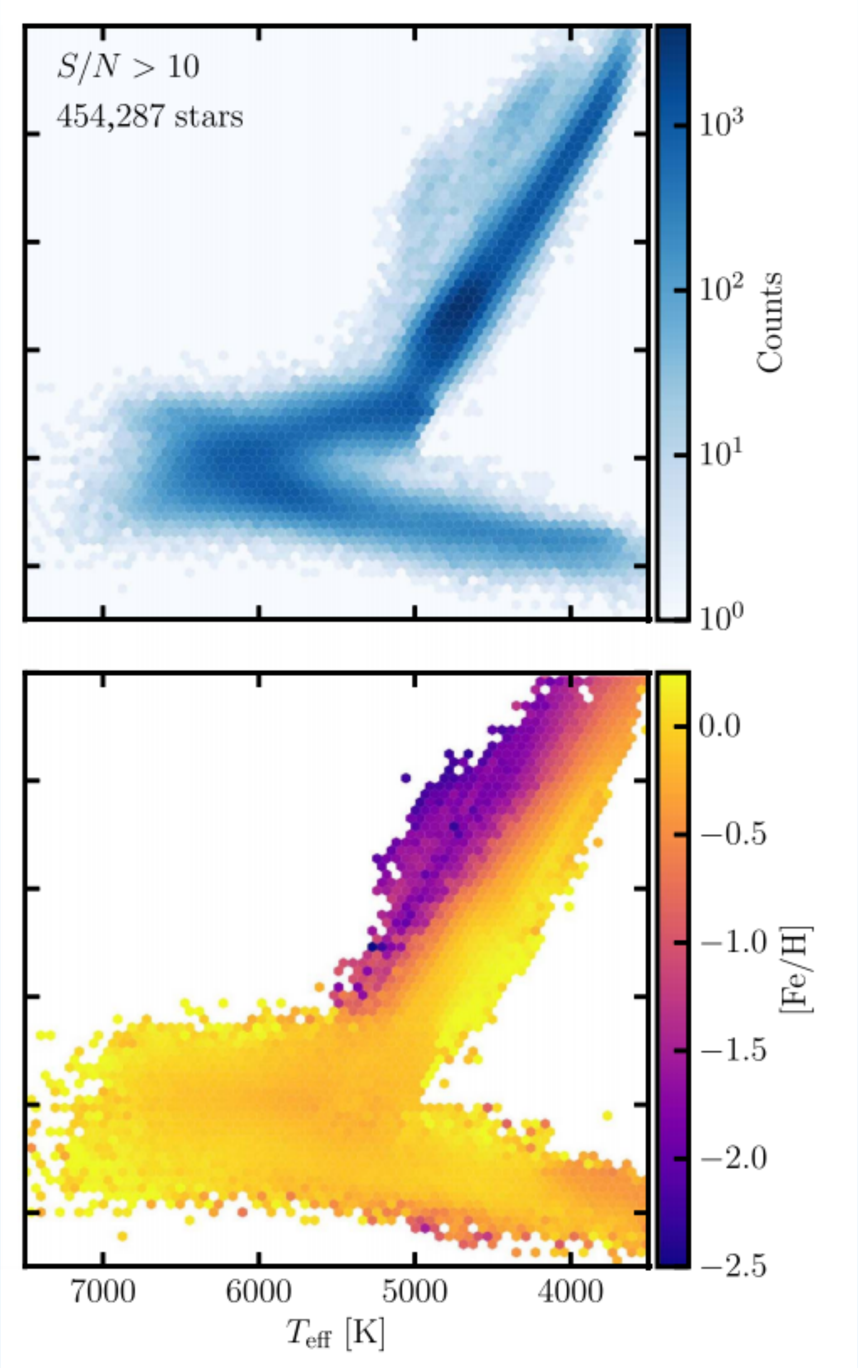
Climbing down the metallicity ladder



[Fe/H] < -6.5

The Future: Gaia RVS



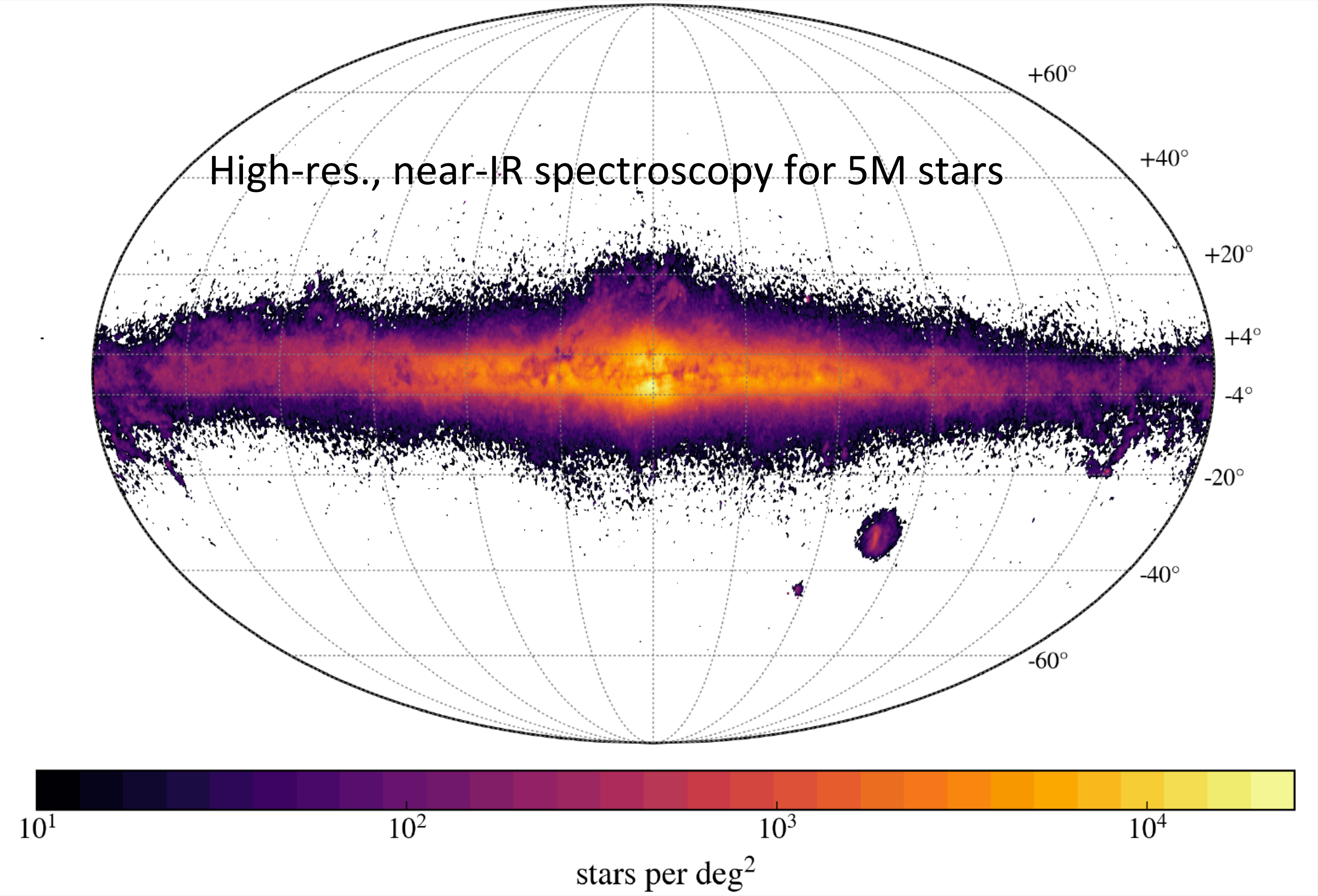


One can derive abundances from this with The Cannon (Casey+2017) – see The RAVE-on Catalog of Stellar Atmospheric Parameters and Chemical Abundances for Chemo-dynamic Studies in the *Gaia* Era – http://adsabs.harvard.edu/abs/2017ApJ...840...59C

RAVE spectra are great to prepare for *Gaia* RVS spectra!

The Future: Sloan V Milky Way Mapper

- Target all stars in the Milky Way with H < 11, G-H > 3.5 - 5 million stars, spanning spatial area ~3000 deg^2



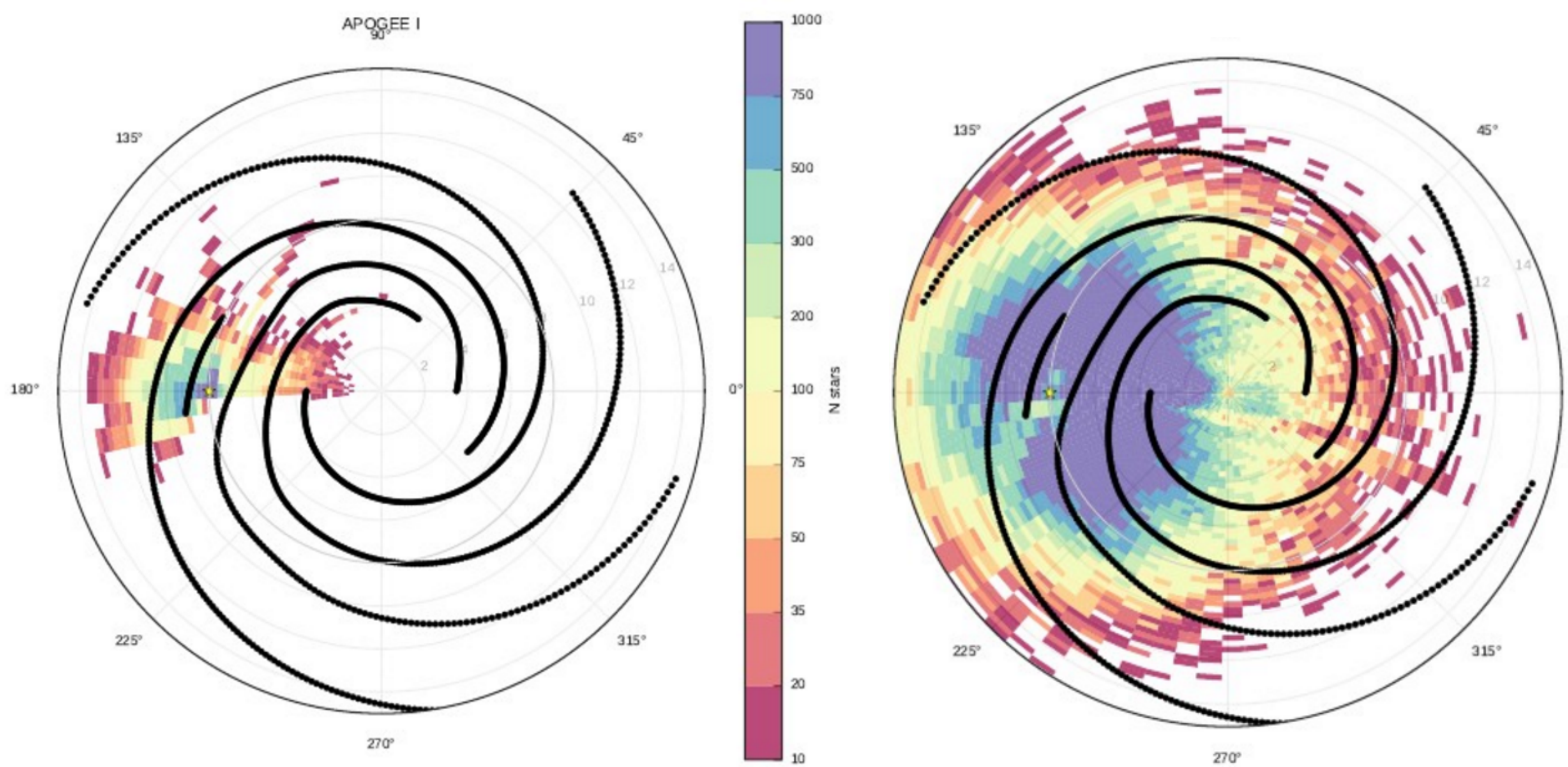
This image shows the density of spectra

Sven Buder (MPIA)

The Future: Sloan V Milky Way Mapper

APOGEE: 250K stars

Milky Way Mapper:
5 million stars



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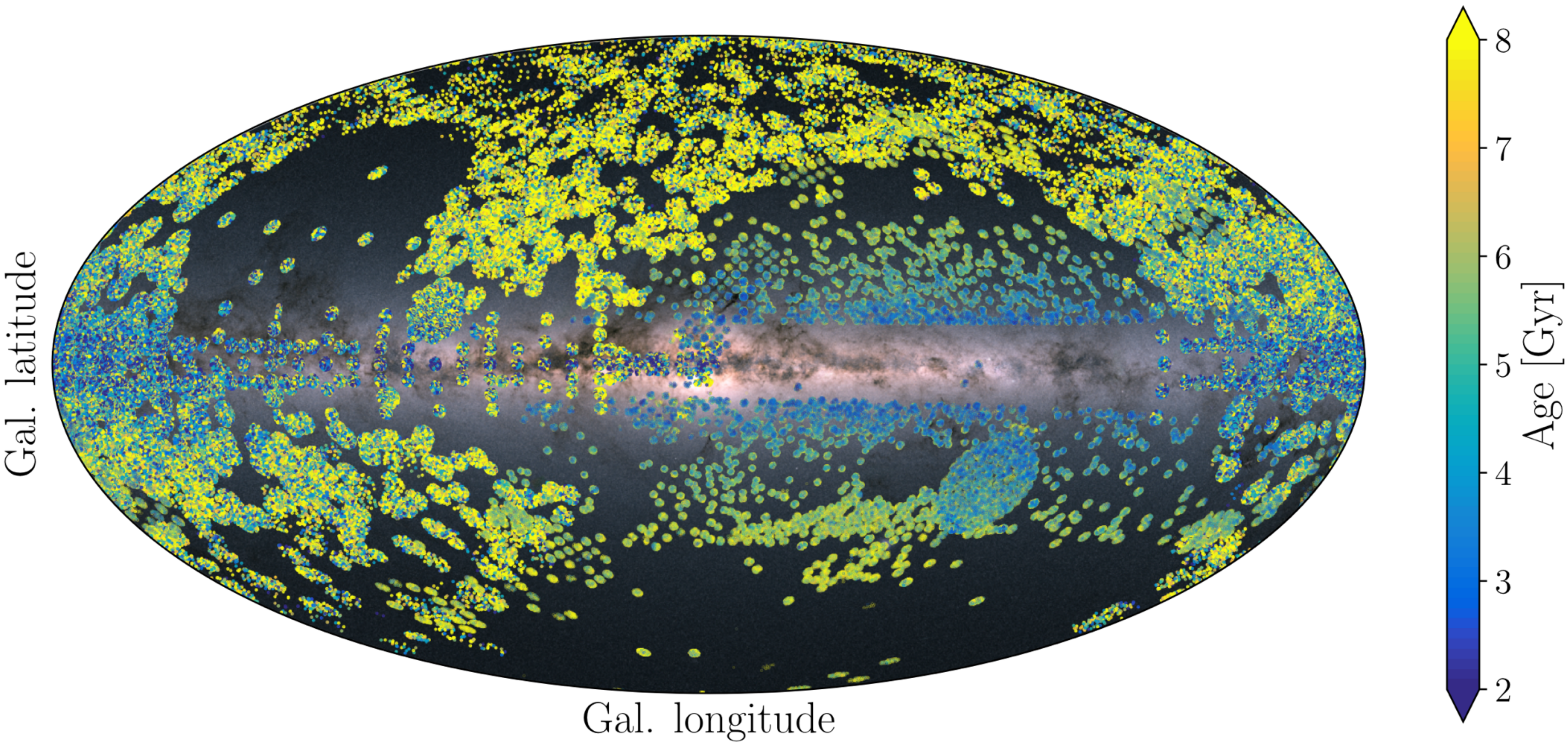
The Future: Sloan V Milky Way Mapper

Milky Way "Model A"
Mark Rothko *Orange and Yellow*

Milky Way Model B
Jean-Michel Basquiat *Untitled*

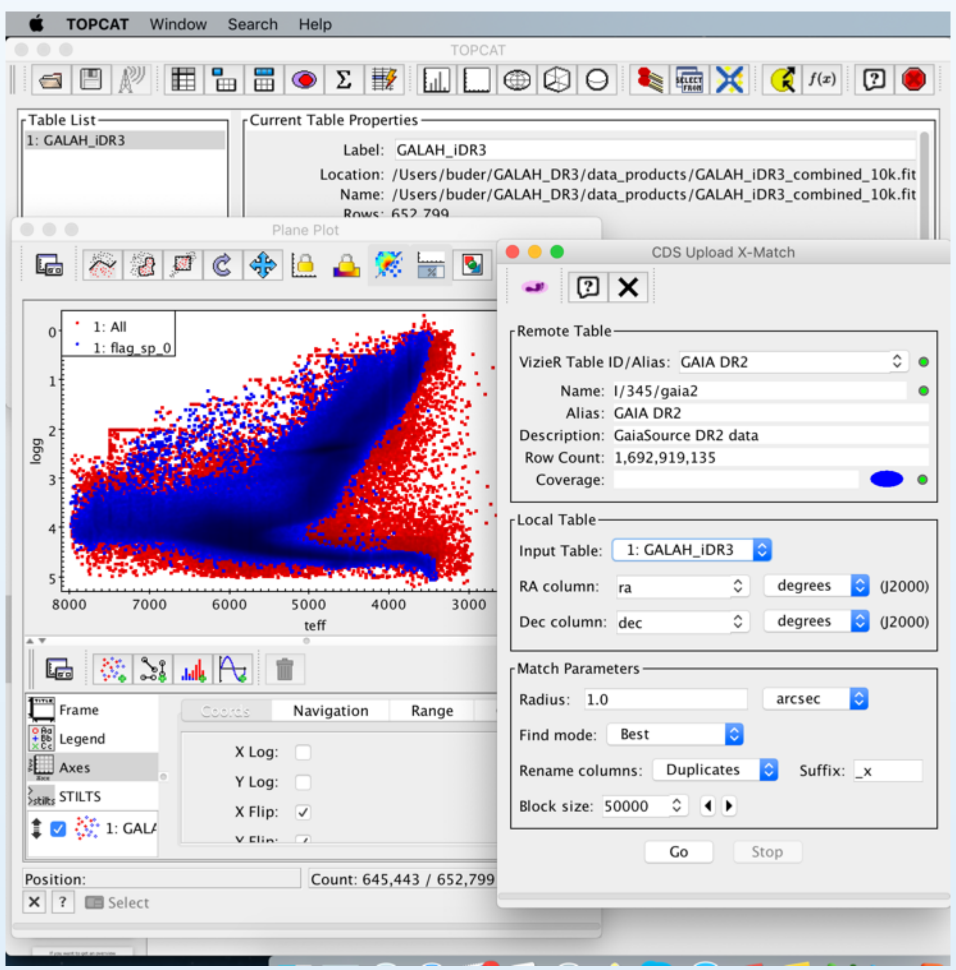
The Future: Chemodynamic cartography

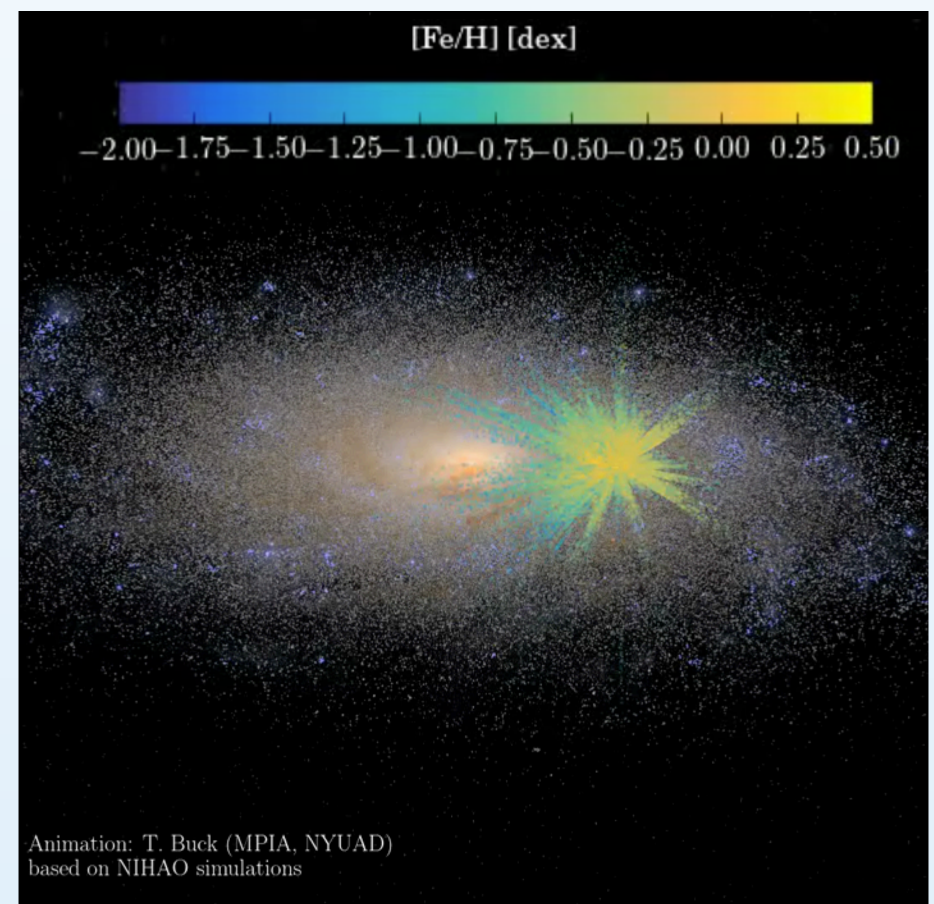


Ages from Ness+16 (APOGEE), Ho+16 (LAMOST), Buder+ in prep. (GALAH)

Take home

- We will have surveys of many, many millions of spectra by 2025
- Can use current data (age/chemistry/orbits) to make predictions, test ideas
- **Ask simple questions,** seek to answer those questions, expect to develop methods, and dig into data very deeply along the way, always be suspicious of systematics.





http://www.star.bris.ac.uk/~mbt/topcat/

Sven Buder (MPIA)

Discussion

Which survey can I use for my research idea?

Backup slides

From 1D LTE to 3D non-LTE

~~Hydrostaticity~~
~~Mixing length~~
~~Plane-parallel~~

→

(Magneto-)
Radiation-
Hydrodynamics

1D LTE

~~Boltzmann,~~
~~Saha~~

→

Statistical
equilibrium

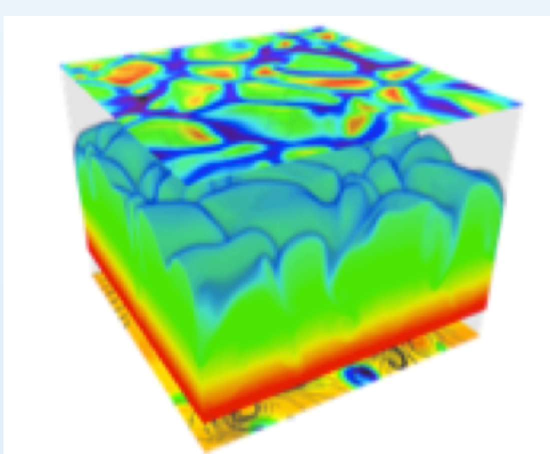
Species not sensitive to NLTE

Species sensitive to NLTE

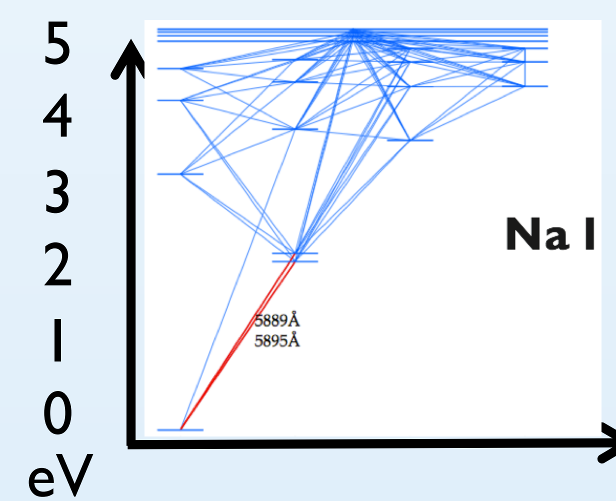
3D LTE

Why bother?

1D NLTE



3D NLTE



Credit: Karin Lind

If you want to get an overview

Bland-Hawthorn & Gerhard (2016)
The Galaxy in Context: Structural, Kinematic, and Integrated Properties
http://adsabs.harvard.edu/abs/2016ARA%26A..54..529B

Rix & Bovy (2013)
The Milky Way's stellar disk. Mapping and modeling the Galactic disk
http://adsabs.harvard.edu/abs/2013A%26ARv..21...61R

Jofré, Heiter, & Soubiran (2018)
Accuracy and precision of industrial stellar abundances
http://adsabs.harvard.edu/abs/2018arXiv181108041J

Nissen & Gustafsson (2018)
High-precision stellar abundances of the elements: methods and applications
http://adsabs.harvard.edu/abs/2018A%26ARv..26....6N

So many unknowns - just take the disk...

Age is a fundamental variable of temporal evolution - for a given age, what is the variability in orbits? What is the variability in abundances? How does this change across the Galaxy?

How well mixed was the gas from which the stars formed? Radially, azimuthally? How much variability is there in abundances for stars born in a small radial annuli?

Was the disk really formed from ensembles of open clusters as expected under the umbrella of chemical tagging (e.g. Freeman & Bland-Hawthorn 2002)?

http://adsabs.harvard.edu/abs/2002ARA%26A..40..487F

Where we are going

- We will have surveys of many, many millions of spectra by 2025
- Can use current data to make predictions, test ideas
- **Ask simple questions,** seek to answer those questions, expect to develop methods, and dig into data very deeply along the way, always be suspicious of systematics.
- I will present a few large surveys and some major advances from them… but there is much, much more opportunity
- very few papers exist that look at individual abundances (apart from outliers, but what about the entire disk and bulge?), very little to understand halo in its fine abundance detail, very little to understand orbit+chemistry, very little done with binaries…

Stellar properties from spectra

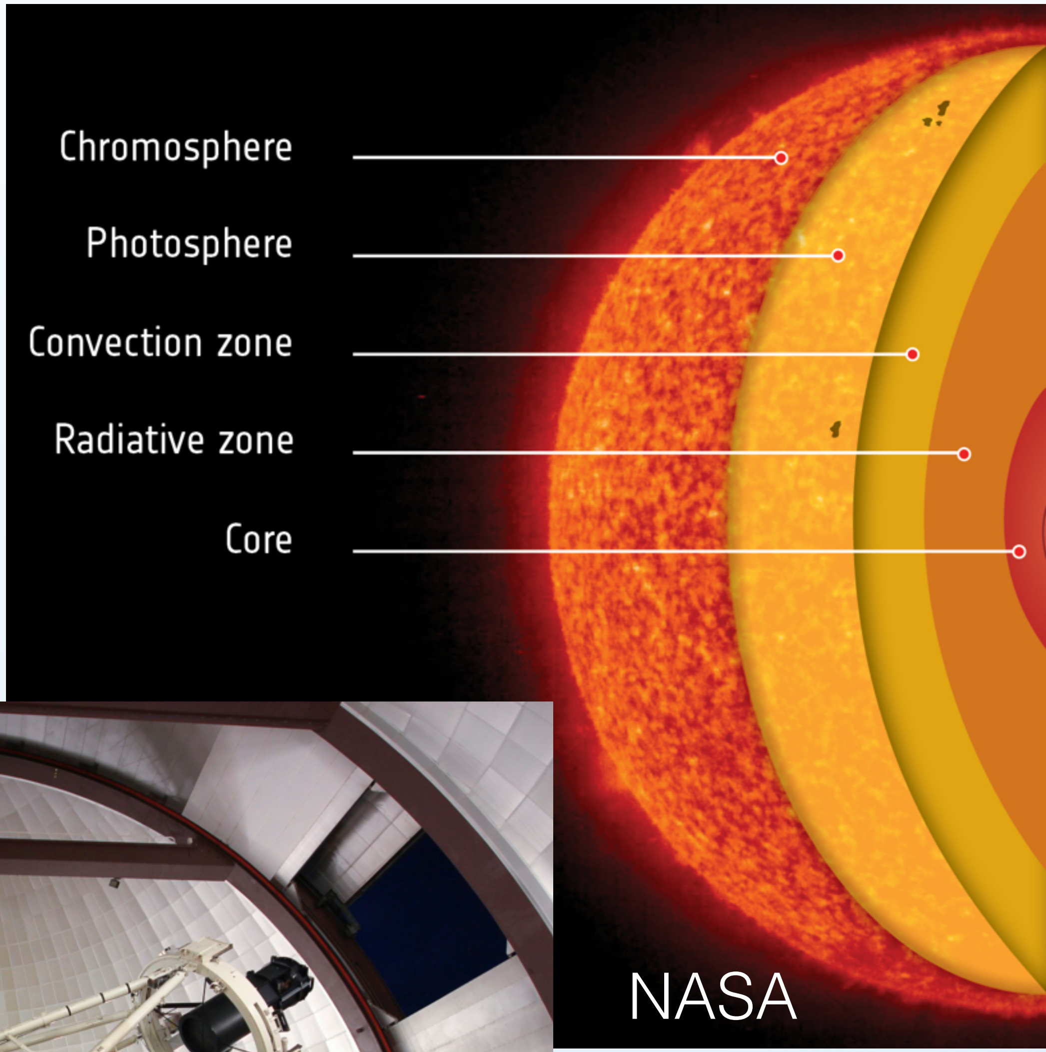
Thermodynamic quantities / gradients
(temperature, pressure, …)

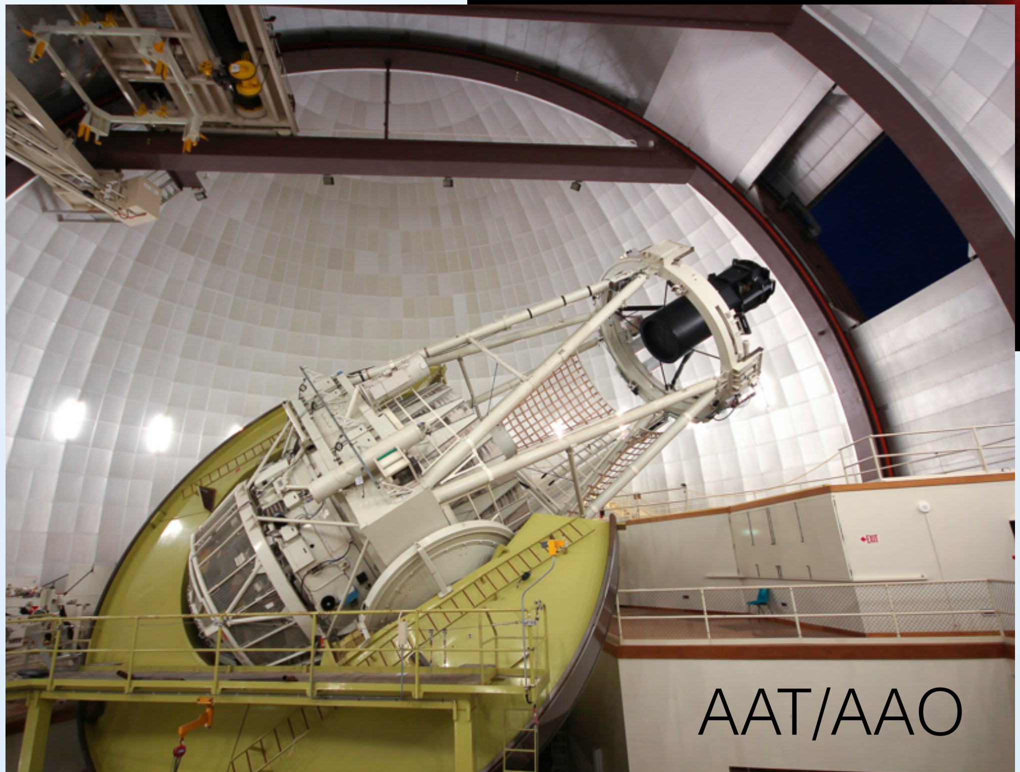
Chemical composition
(Hydrogen, helium, “metals” = the rest*)

Turbulences (broadening)

Sources between
star & telescope
(interstellar medium, earth’s
atmosphere)

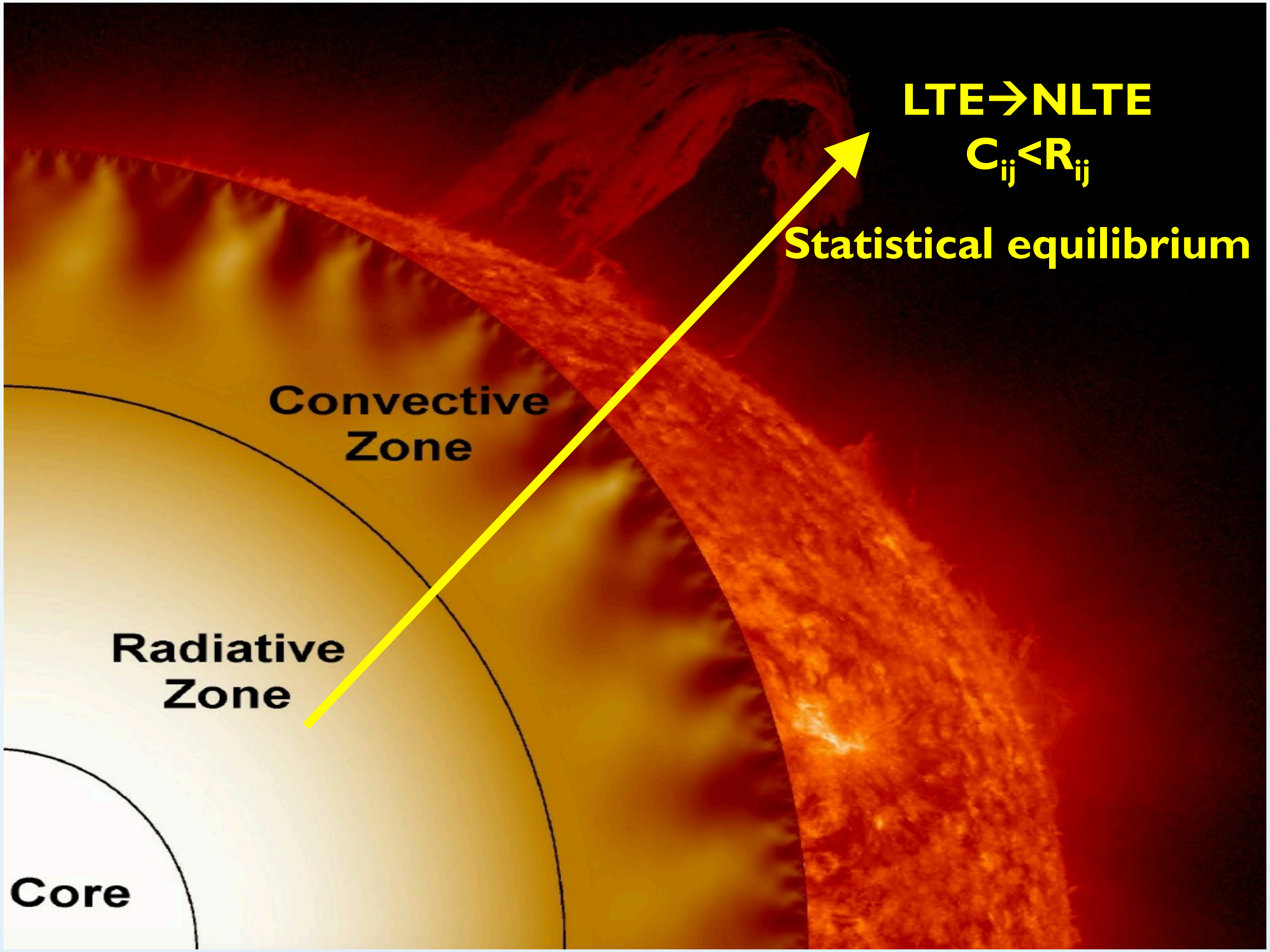
Influences of
the observation setup
(Instrument resolution)





*yes, in stellar spectroscopy carbon, oxygen etc. are metals!

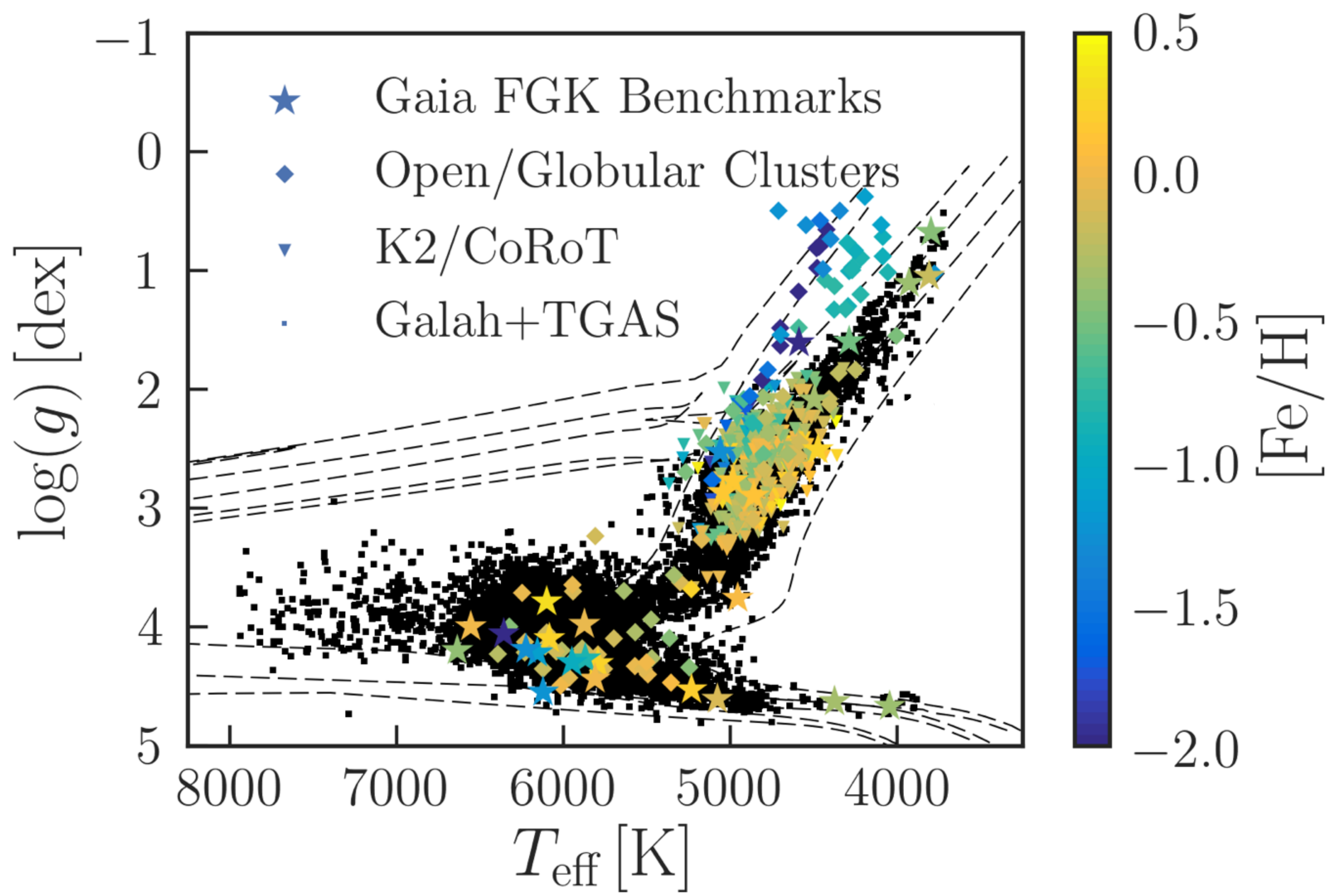
Why NLTE?



LTE→NLTE
$C_{ij}<R_{ij}$
Statistical equilibrium
Convective Zone
Radiative Zone
Core

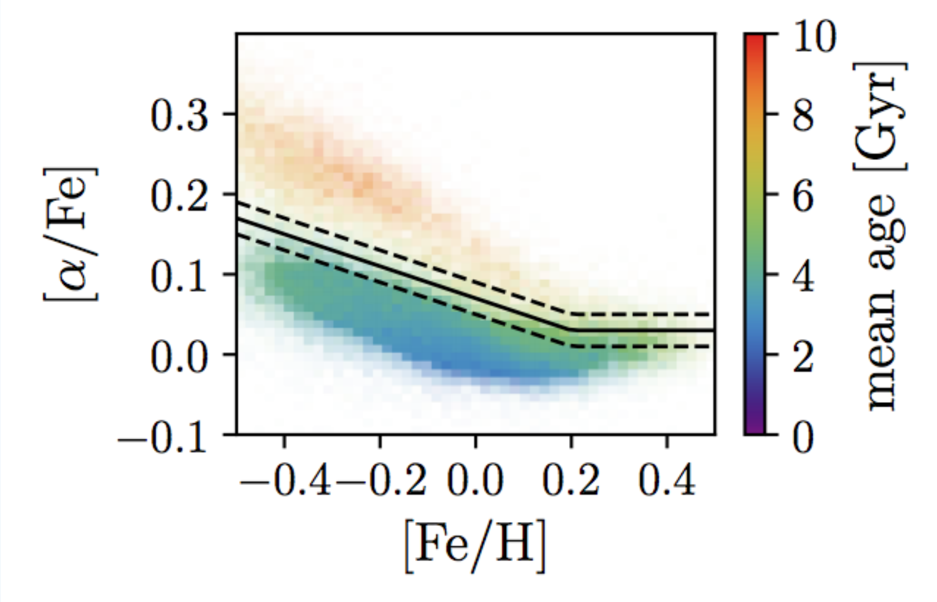
We need to improve our accuracy!

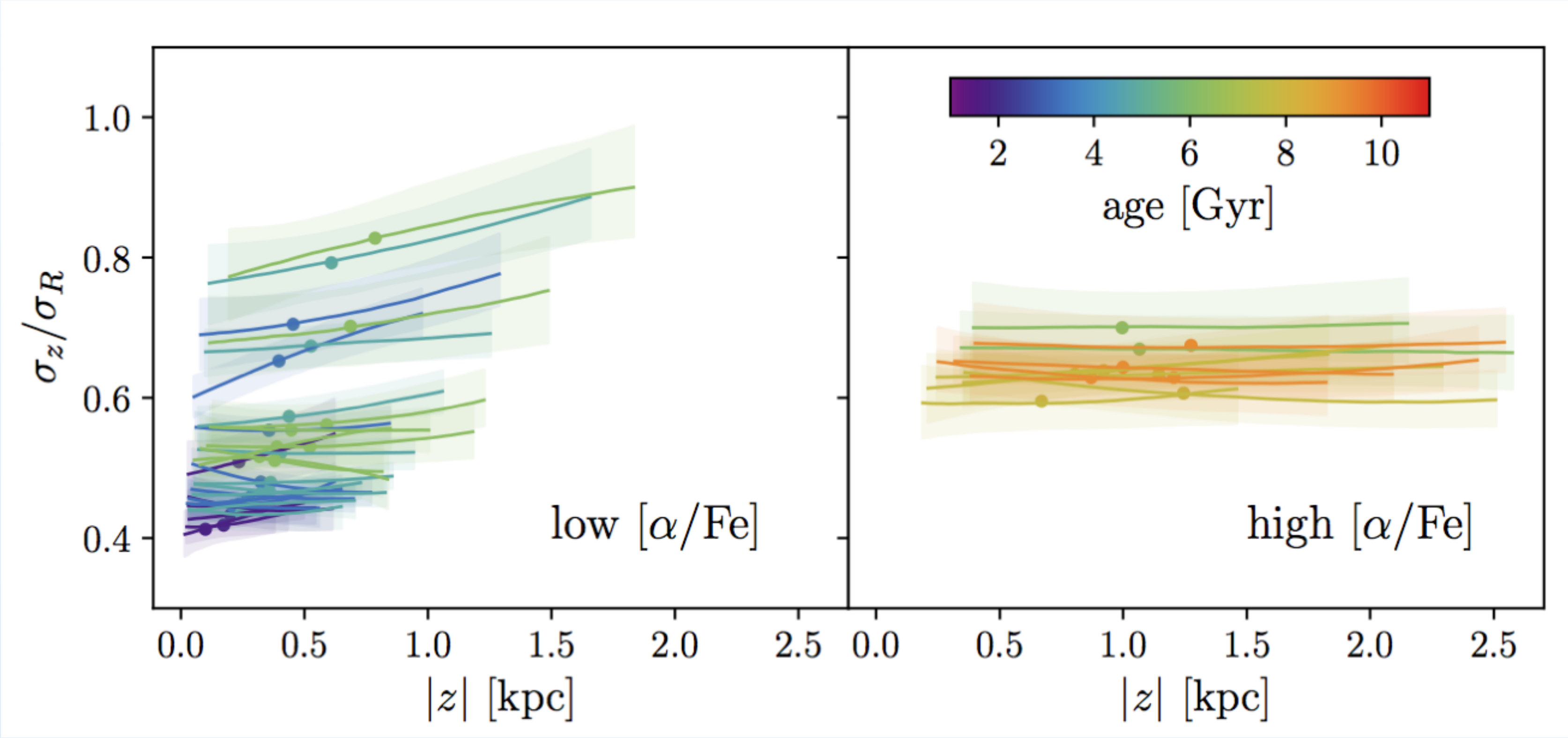
validation/calibration with non-spectroscopic information



Advances with APOGEE — Temporal evolution of the Milky Way

Dynamical heating across the Milky Way disc using APOGEE and Gaia
Mackereth+ 2018 **(mono-age, mono-[Fe/H] populations)**
http://adsabs.harvard.edu/abs/2019arXiv190104502M





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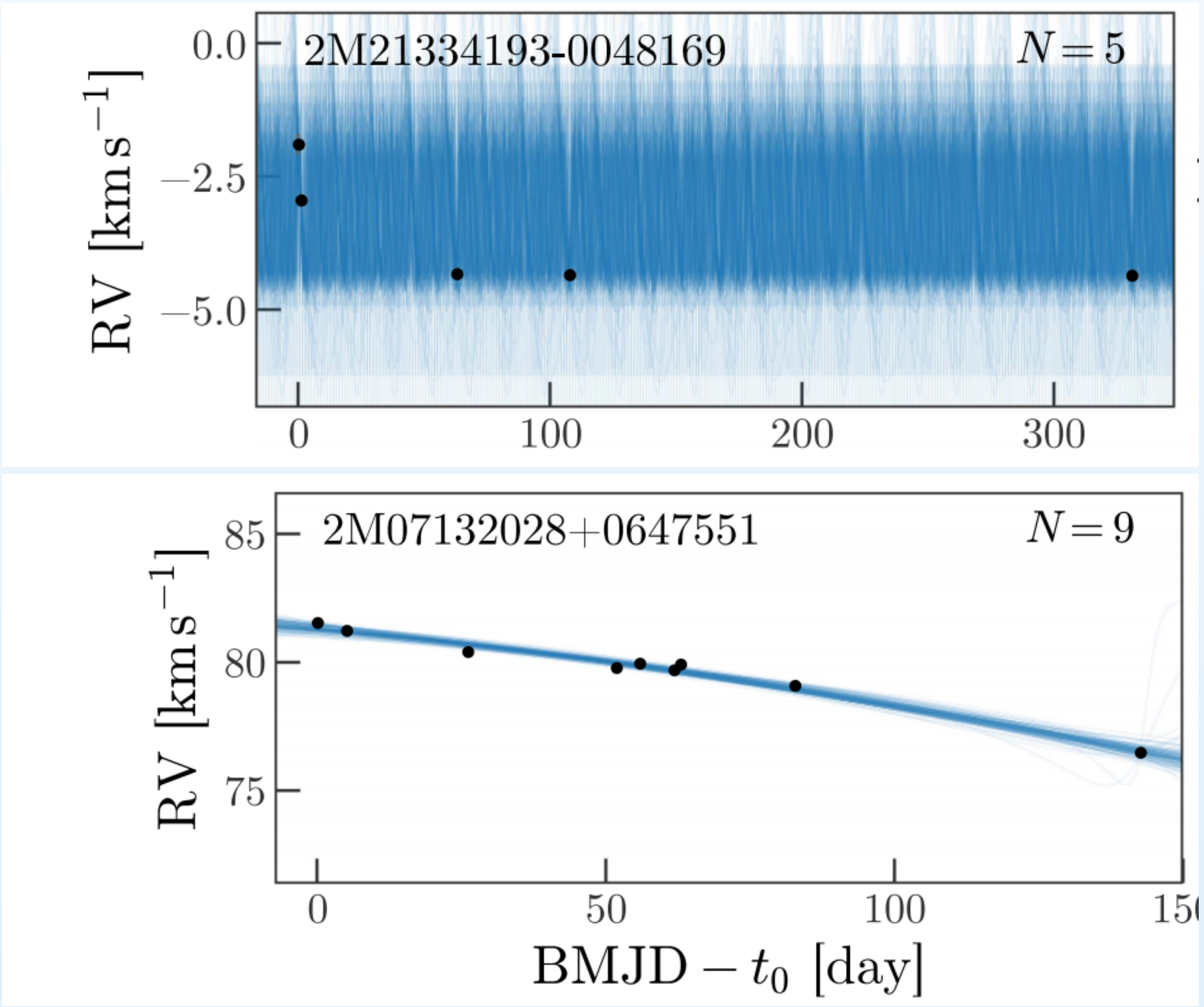
Advances with APOGEE — binary systems

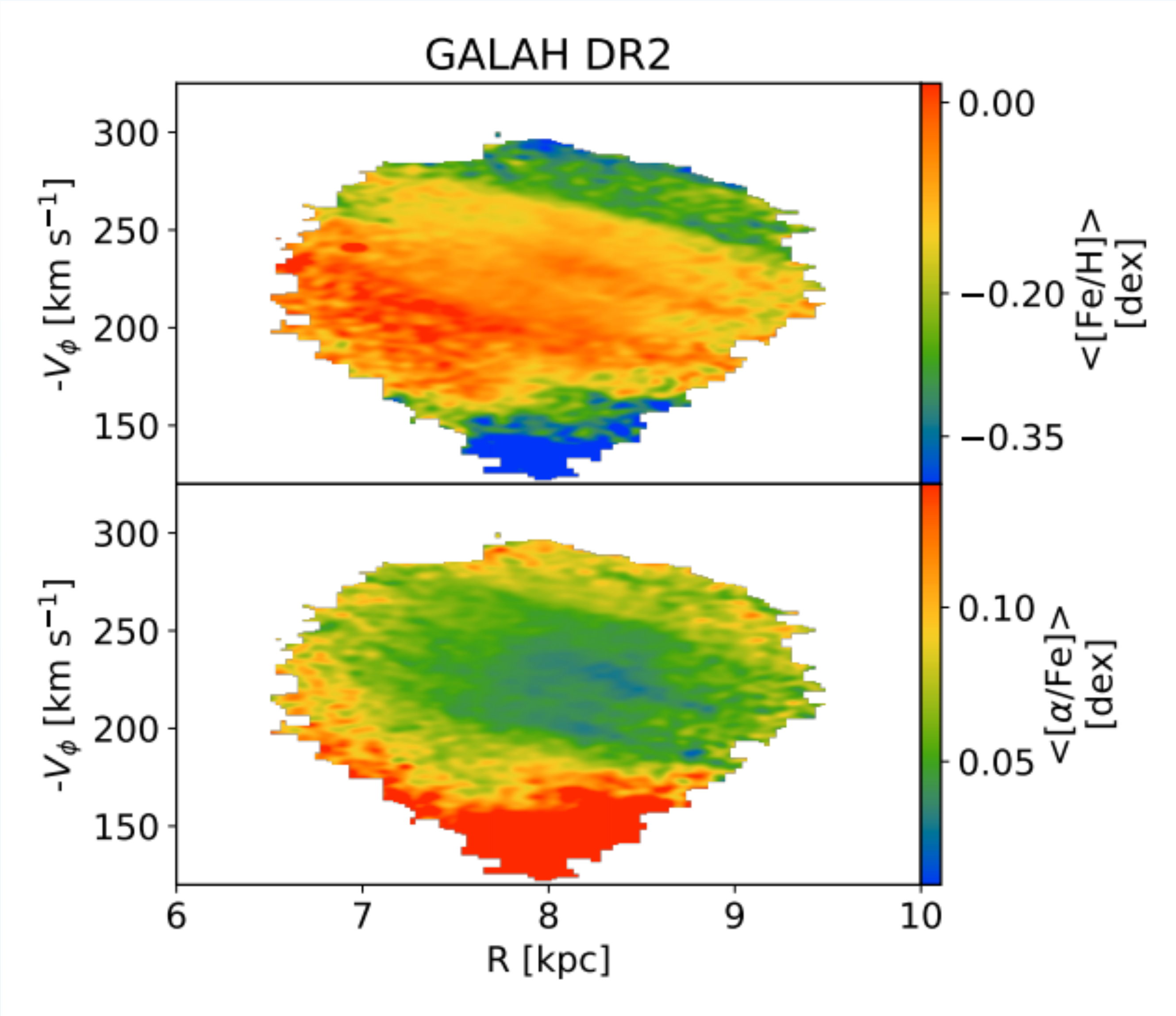
Binary Companions of Evolved Stars in APOGEE DR14: Search Method and Catalog of ~5000 Companions, Price-Whelan+ 2018
http://adsabs.harvard.edu/abs/2018AJ....156...18P

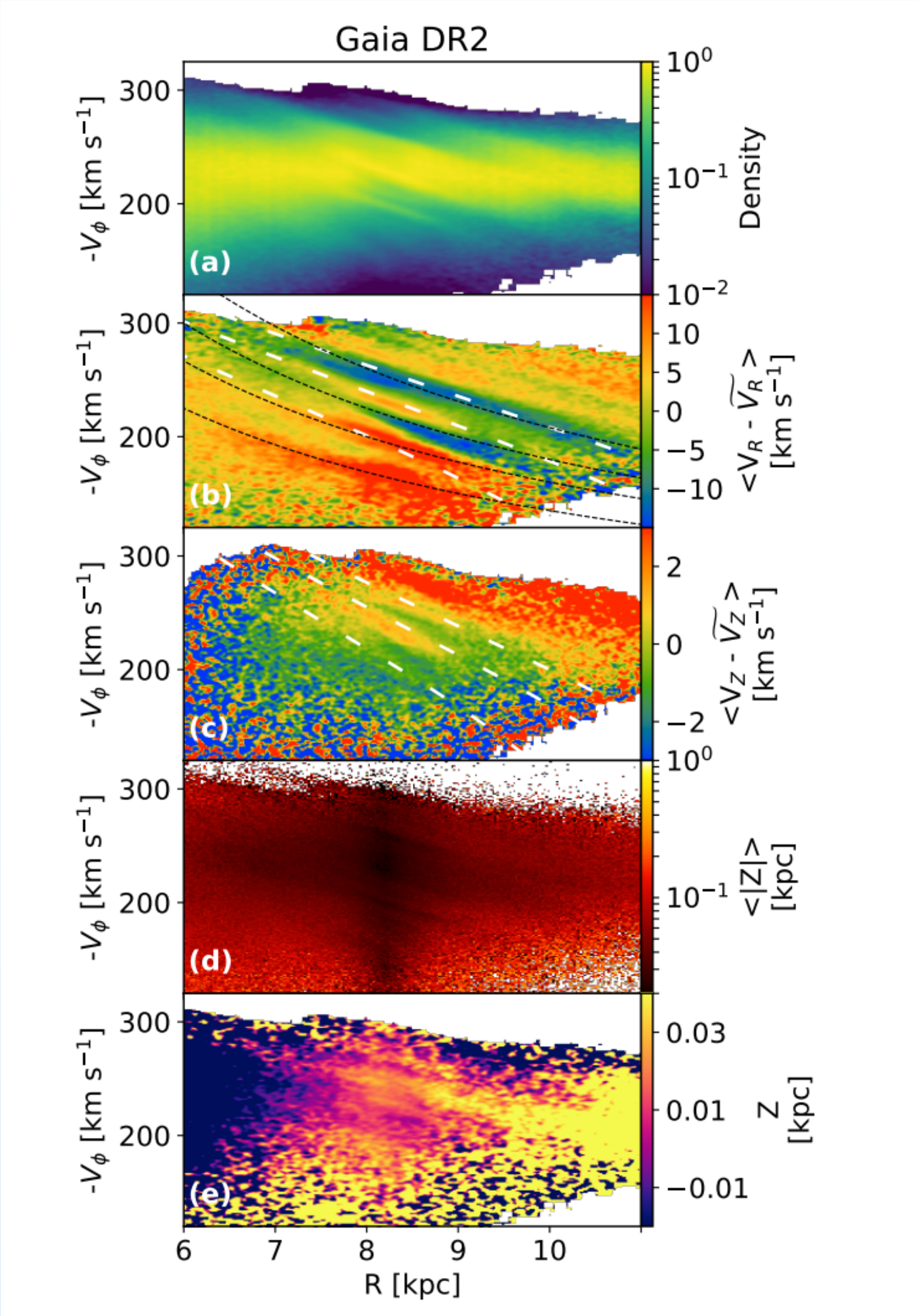


The Joker - full posteriors of orbital solutions based on RV variability

Advances with GALAH data — phase spiral characterisation

- The GALAH survey and Gaia DR2: Linking ridges, arches and vertical waves in the kinematics of the Milky Way Khanna+ 2019 https://arxiv.org/pdf/1902.10113.pdf





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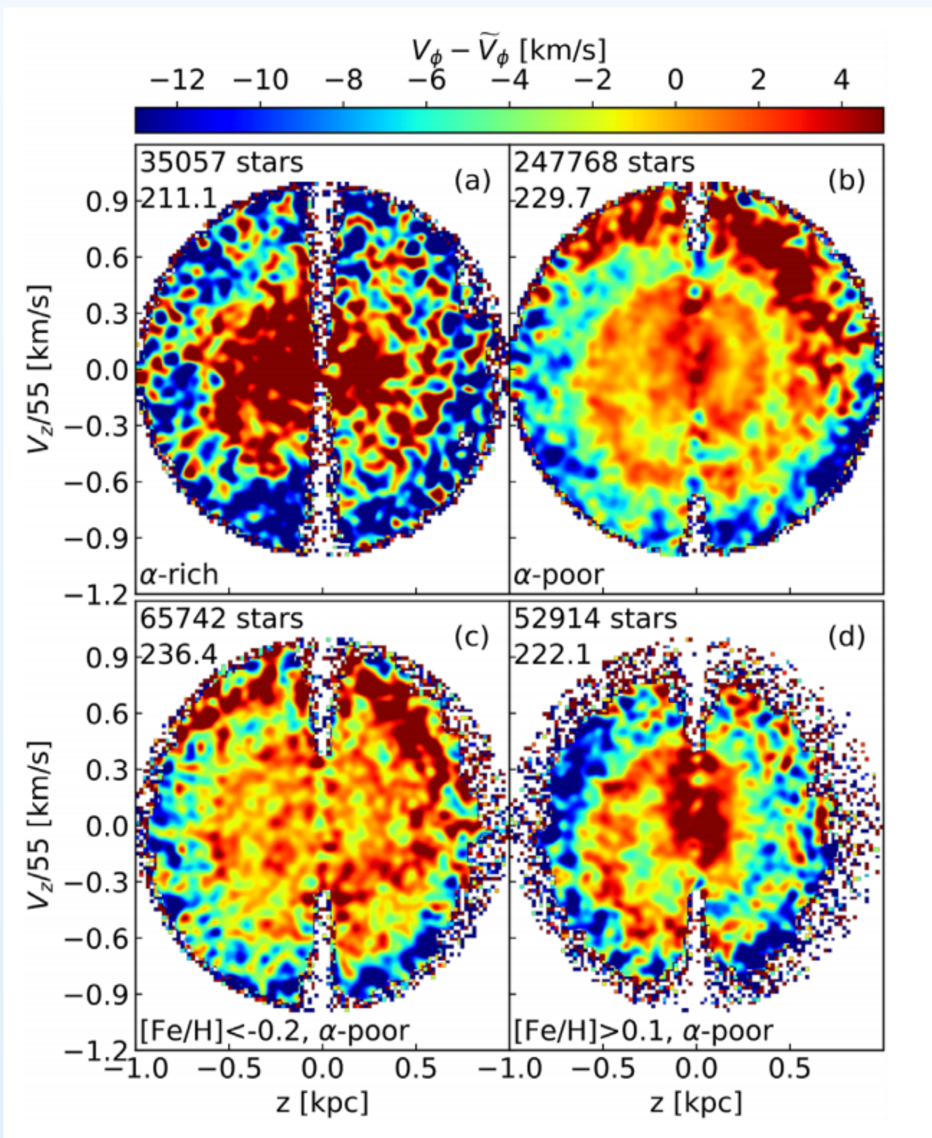
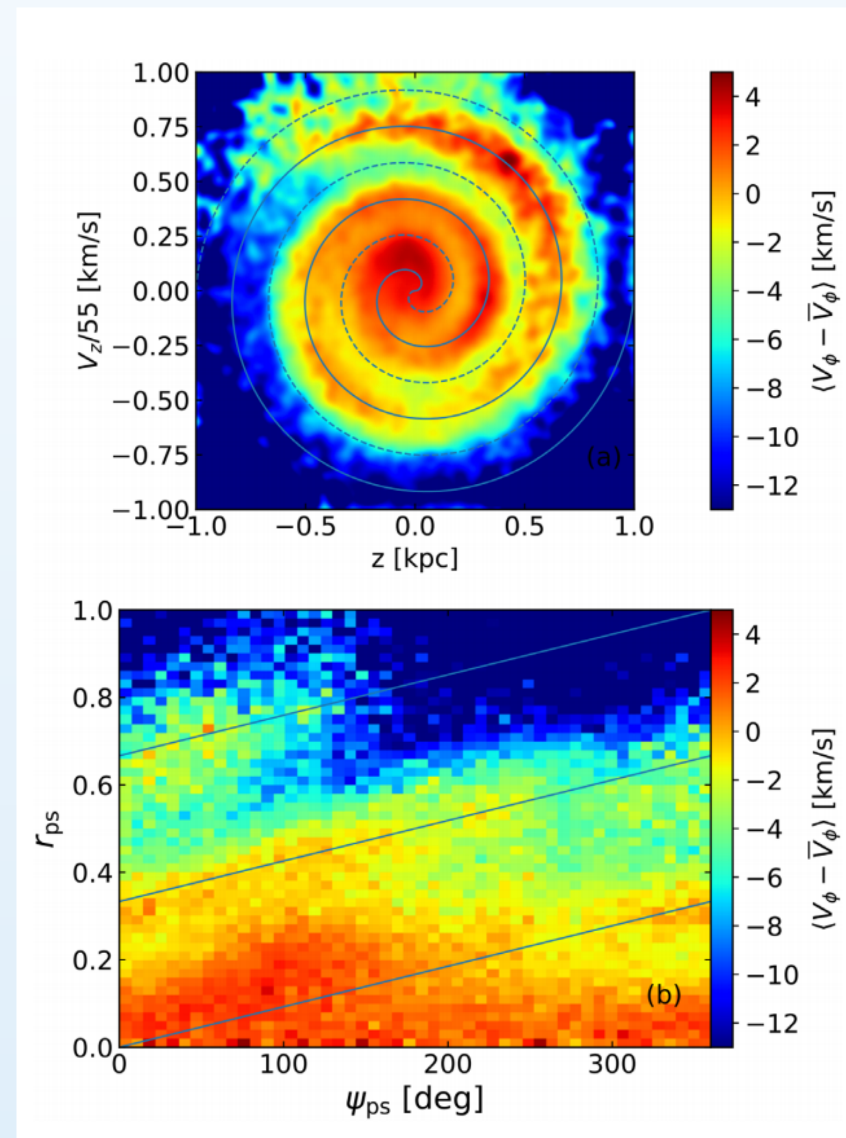
Advances with GALAH data – non-equilibrium signatures

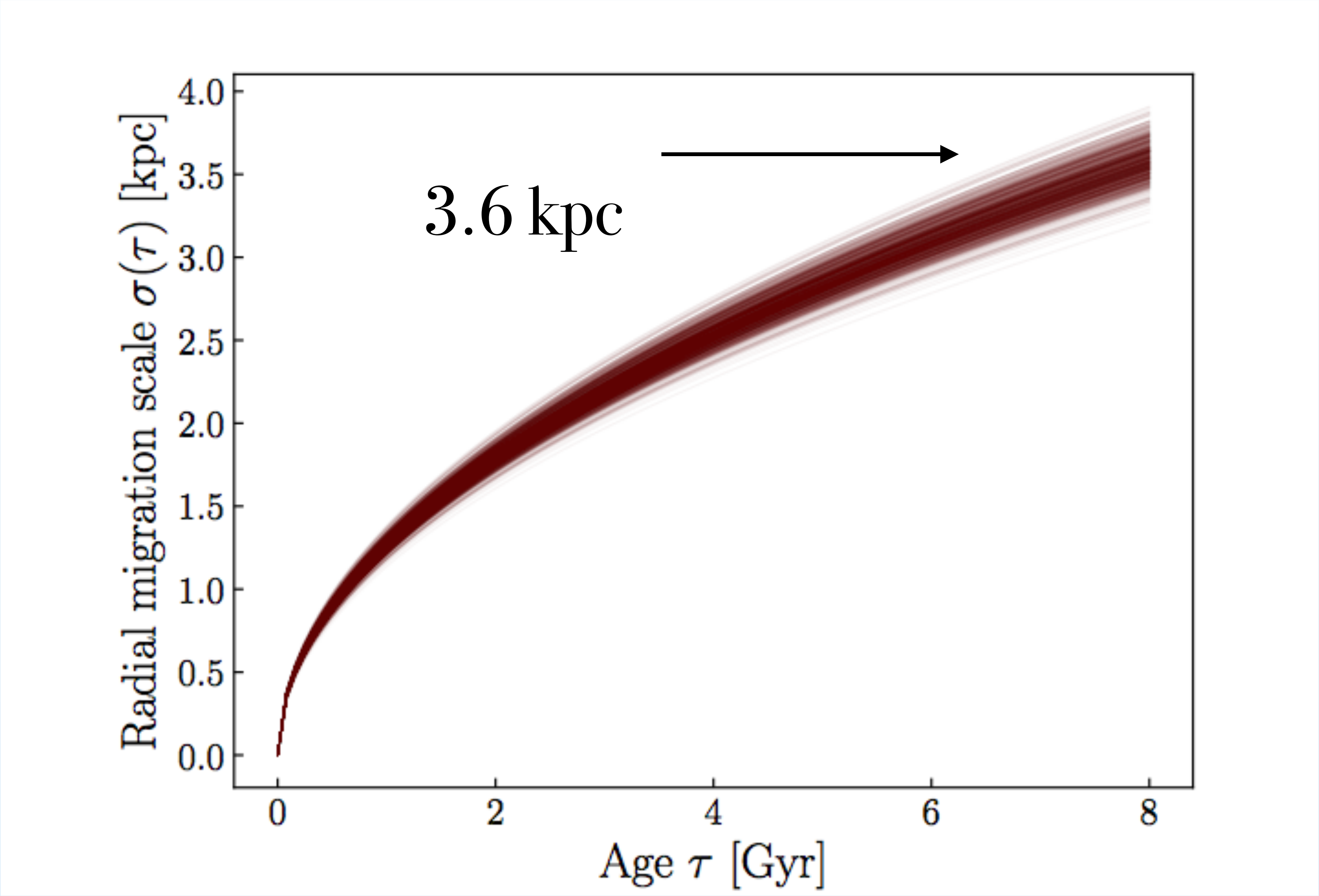
- See Teresa's lecture and her paper: http://adsabs.harvard.edu/abs/2018Natur.561..360A
- The GALAH survey and Gaia DR2: dissecting the stellar disc's phase space by age, action, chemistry, and location, Bland-Hawthorn 2019: http://adsabs.harvard.edu/abs/2019MNRAS.486.1167B





First quantification of Radial Migration in the Milky Way

- model parameterizes the possible star formation and enrichment histories, radial birth profiles, combines this with a migration model

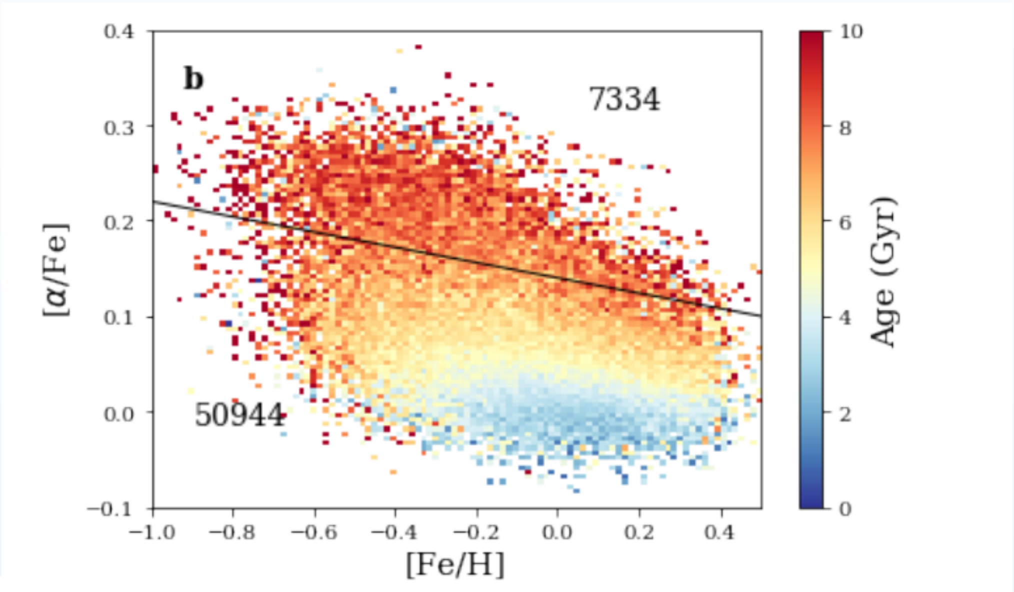


model fit using MCMC to the observed age--metallicity distribution

Frankel et al., 2018

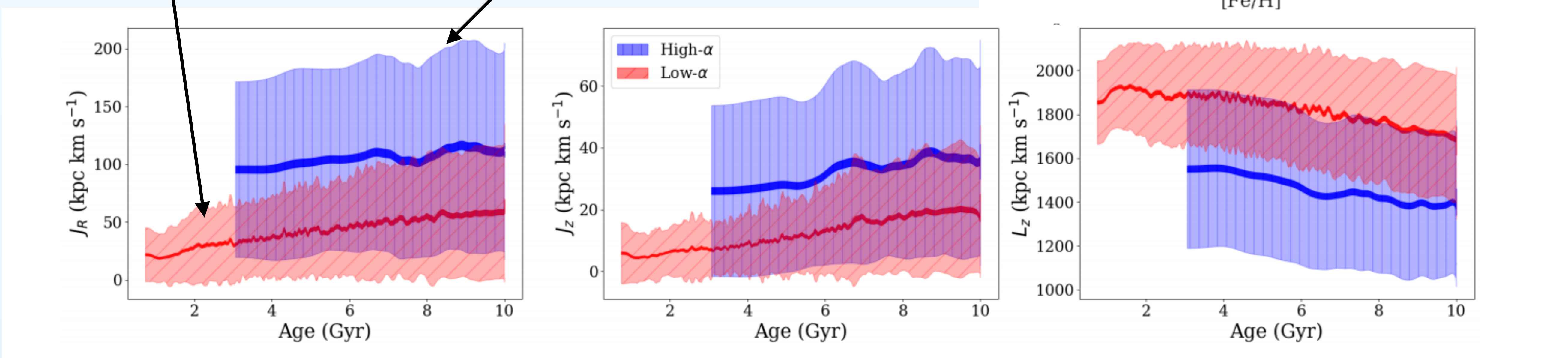
What sets the orbit of a star: age or chemistry?

JR: Radial Action → eccentricity
Jz: Vertical Action → height above plane
Jφ (or Lz): Angular Momentum →orbital radius



low-α LAMOST stars

high-α LAMOST stars



A star's membership in the high- or low-α sequence indicates its dynamical properties at a given time

Implies separate formation and evolutionary histories for the two sequences

Gandhi & Ness, 2019
http://adsabs.harvard.edu/abs/2019arXiv190304030G