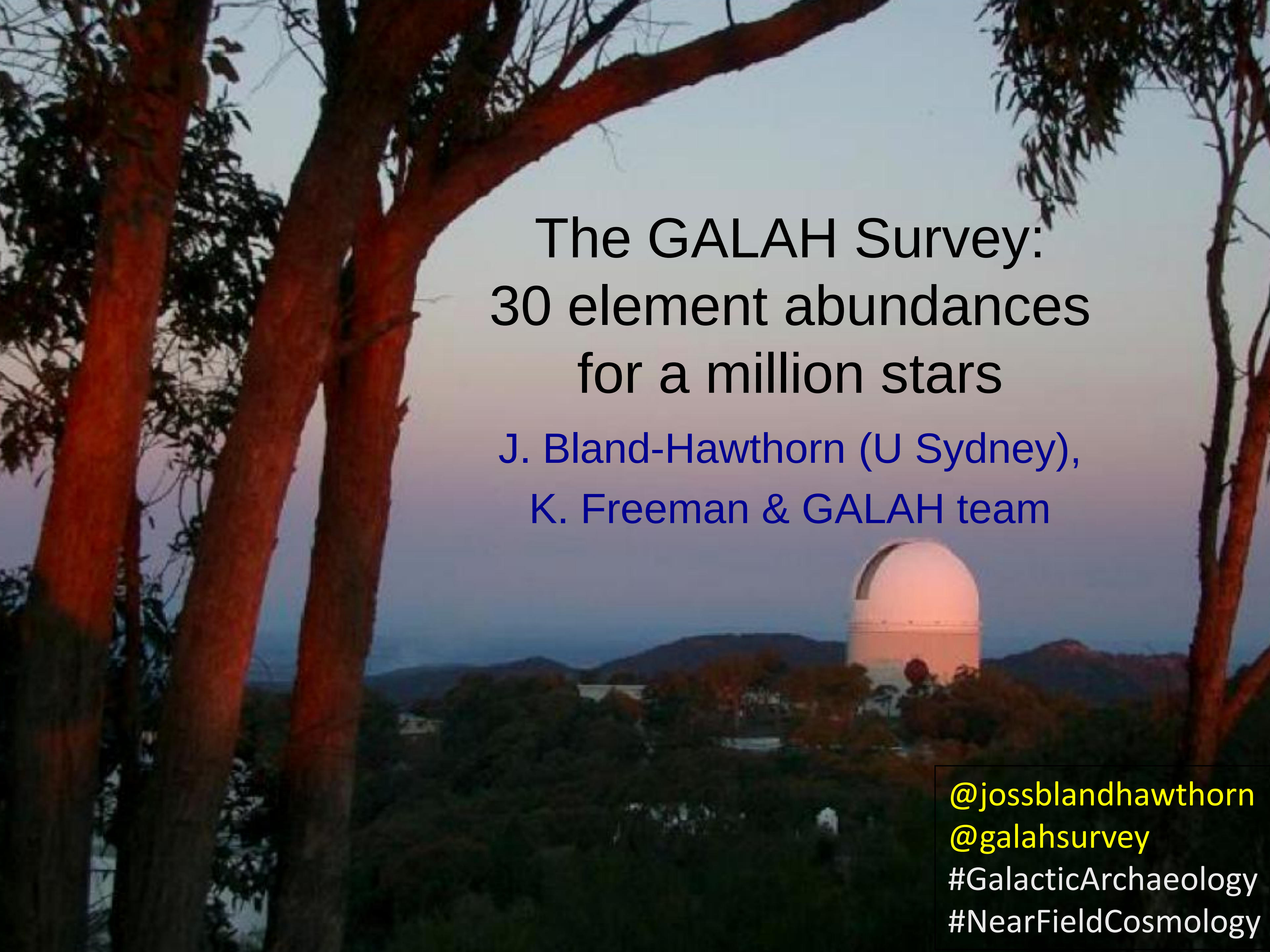


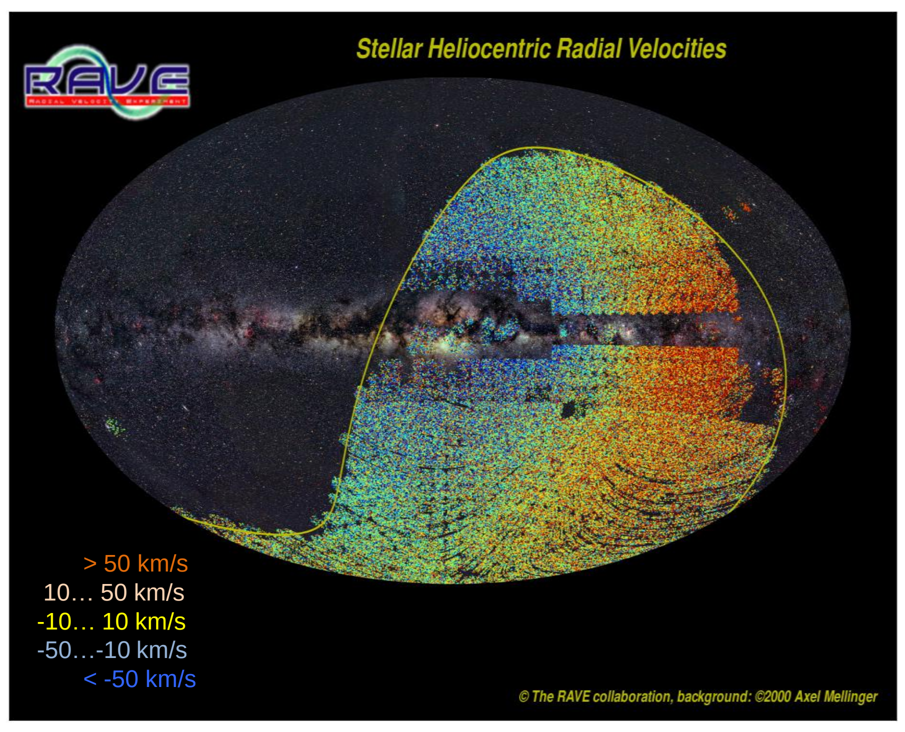
The GALAH Survey: 30 element abundances for a million stars

J. Bland-Hawthorn (U Sydney),
K. Freeman & GALAH team

@jossblandhawthorn
@galahsurvey
#GalacticArchaeology
#NearFieldCosmology

RAVE: 4th public data release

- Intermediate resolution (R~7500)
- 425 561 stars,
- 482 430 spectra *(DR3: 77 461 stars)*
- 9 < I < 12 mag



Kordopatis et al. 2014 - VizieR

Database:

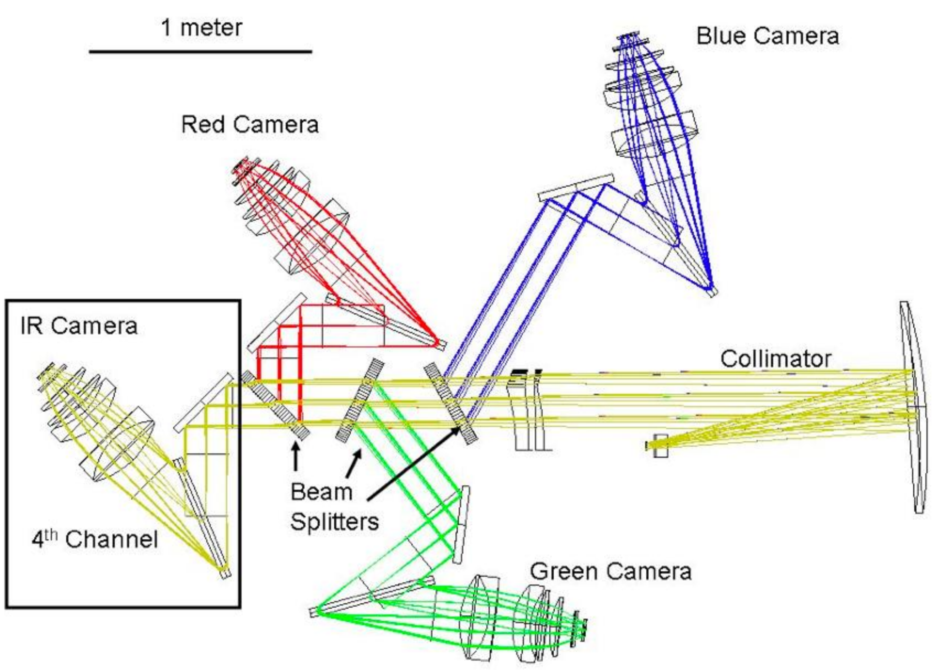
- ✓ **Radial velocities**
- ✓ **Spectral morphological flags**
- ✓ **T_{eff}, logg, [M/H]**
- ✓ ***Mg, Al, Si, Ti, Ni, Fe***
- ✓ **Line-of-sight Distances**
- ✓ **Photometry**:
  DENIS, USNOB, 2MASS, APASS
- ✓ **Proper motions:**
  UCAC4, PPMX, PPMXL, Tycho-2, SPM4

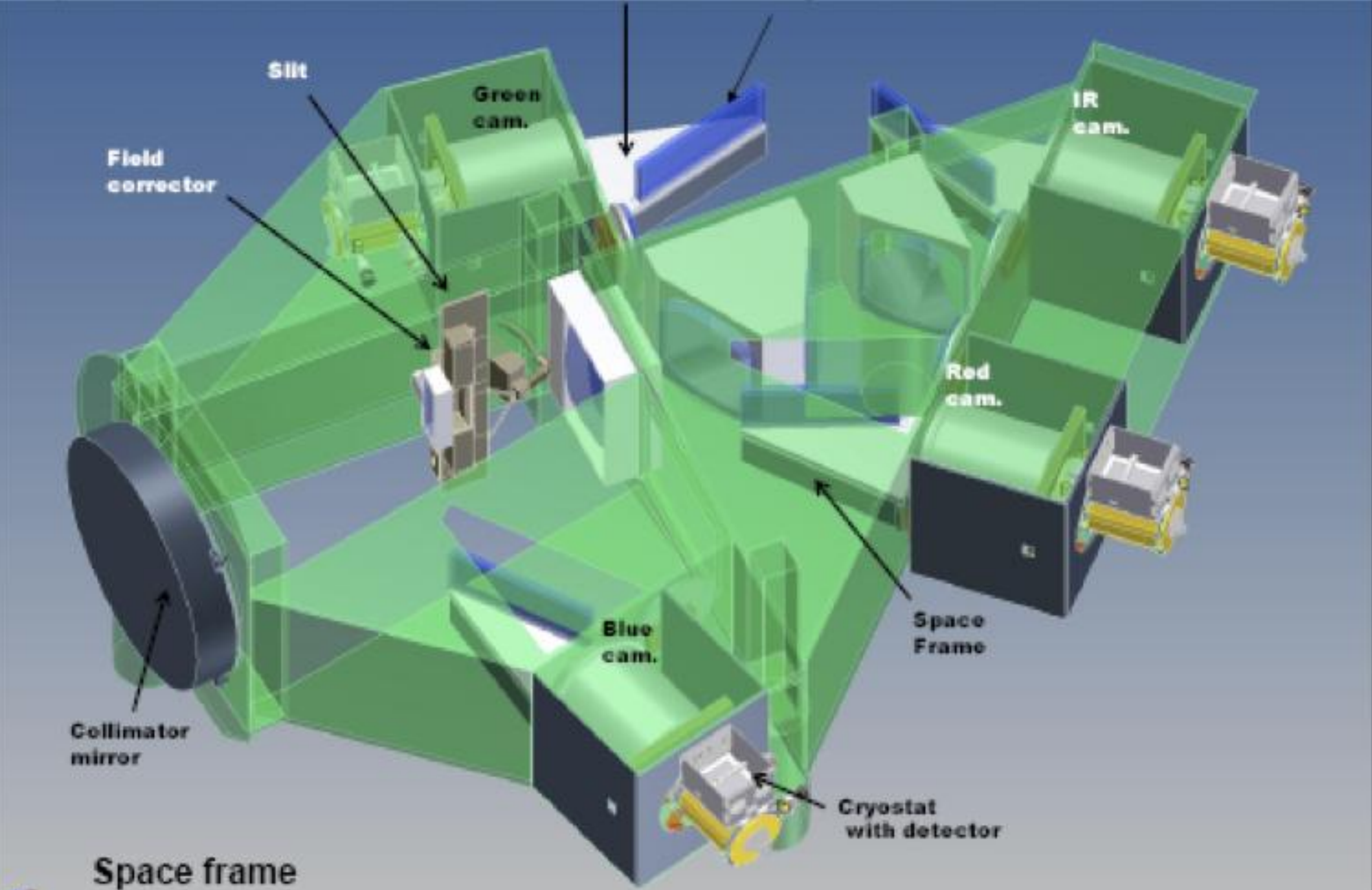
Sharma talk

HERMES @ AAT (first light 2013B)

$12M investment up front: 400 fibres over 2^{o} field, optical

New $12M 4-arm spectrograph, R=30,000 ~250A bands in *bvri*




Slit
Green cam.
Field corrector
IR cam.
Red cam.
Space Frame
Blue cam.
Collimator mirror
Cryostat with detector

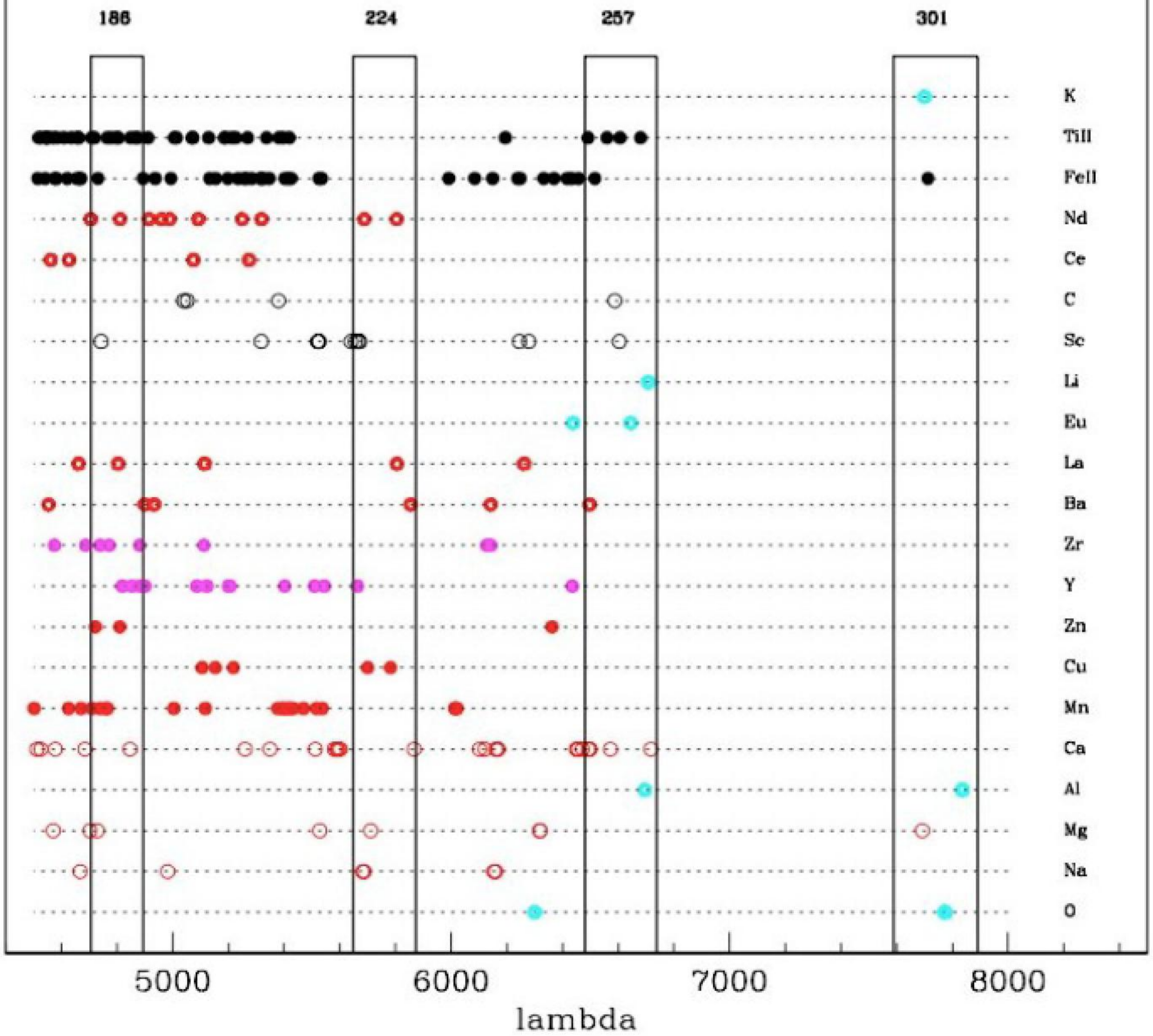
Space frame

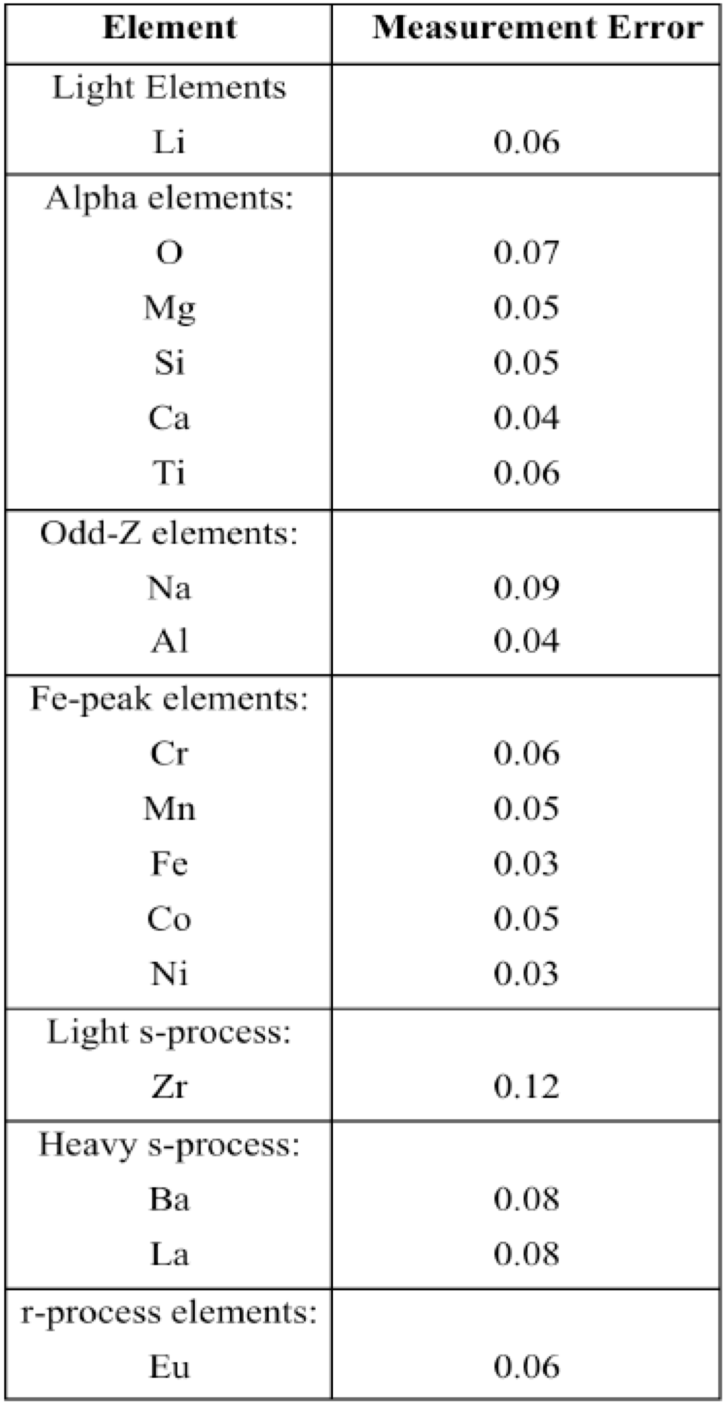
The GALAH survey

- Large observational survey with HERMES @ AAT
- Measuring radial velocity and 30 abundances for **1 million stars** in the Milky Way @ R=30,000 in 4 optical bands
- **Galactic archaeology**: exploring the history of
  - Star formation
  - Chemical evolution
  - Dynamical evolution
  - Minor mergers

  in the Milky Way
- **Near-field cosmology**: use the local environment to get a close-up view of universal processes, esp. early

Single dot can represent multiple lines





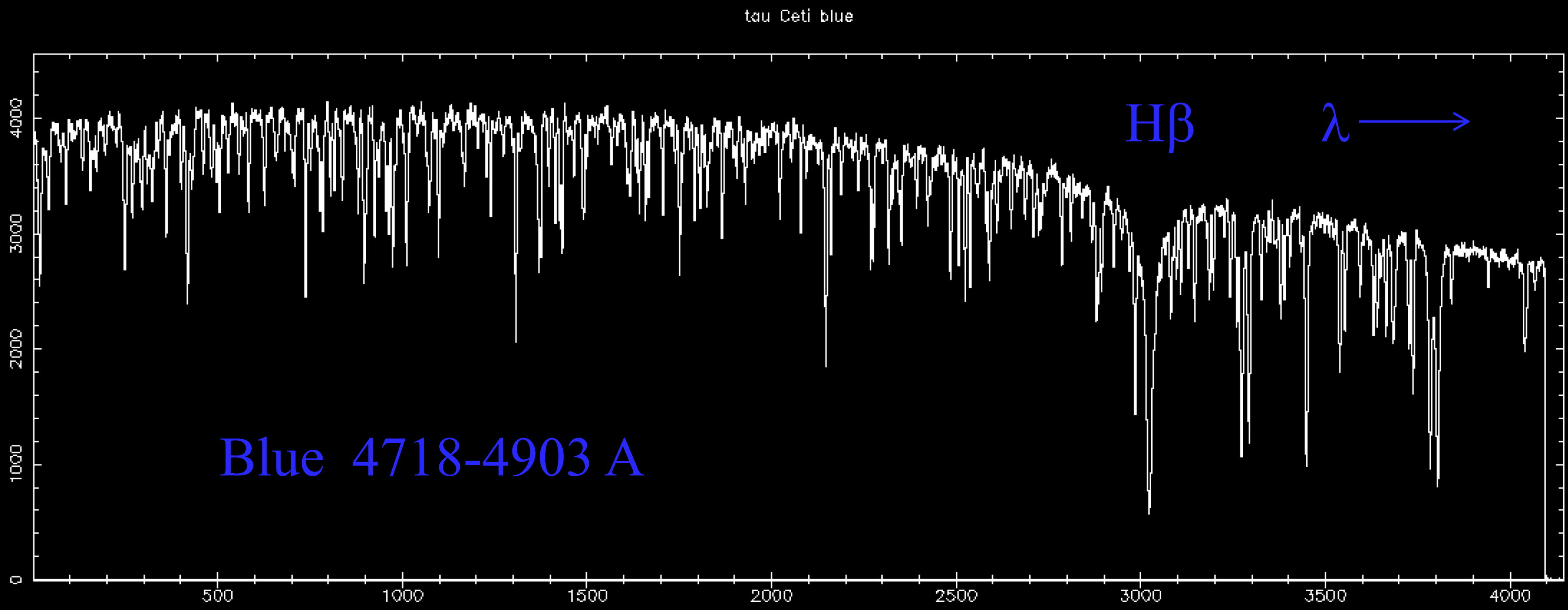
Element	Measurement Error
Light Elements	
Li	0.06
Alpha elements:	
O	0.07
Mg	0.05
Si	0.05
Ca	0.04
Ti	0.06
Odd-Z elements:	
Na	0.09
Al	0.04
Fe-peak elements:	
Cr	0.06
Mn	0.05
Fe	0.03
Co	0.05
Ni	0.03
Light s-process:	
Zr	0.12
Heavy s-process:	
Ba	0.08
La	0.08
r-process elements:	
Eu	0.06

- Abundance accuracy from literature studies using R ~25,000 – 30,000 and SNR ~ 100

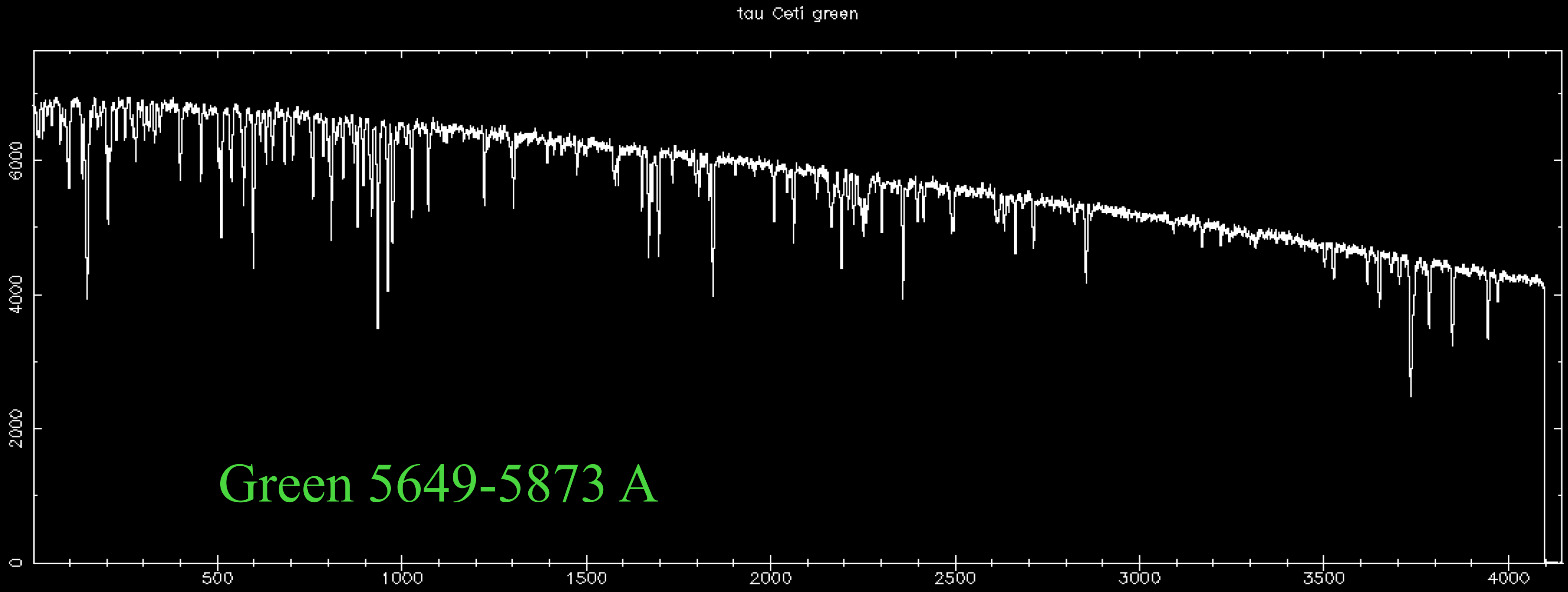
- Measured via 'Equivalent Widths' and / or Spectral synthesis techniques

Best measurements
in star clusters

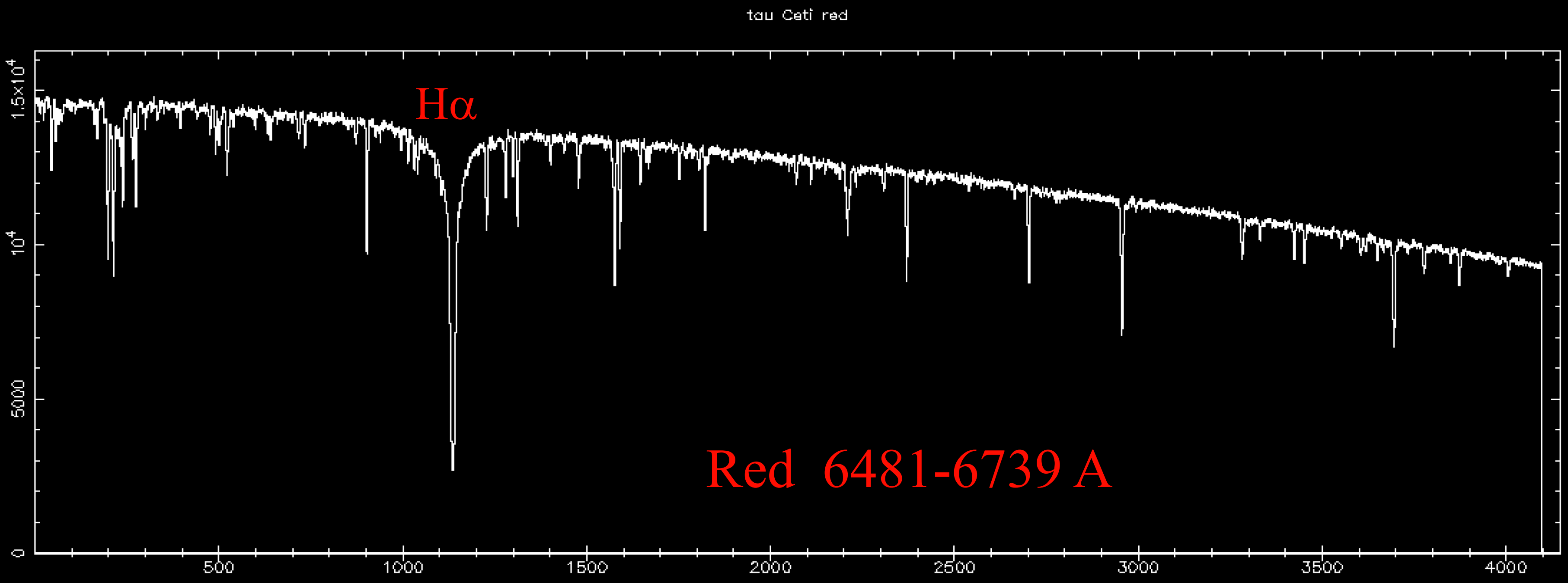
Ref: Pancino et al, 2010; Jacobson et al., 2009;
Carney et al, 2005; Yong, et al., 2005; Friel et al., 2003



Blue 4718-4903 A

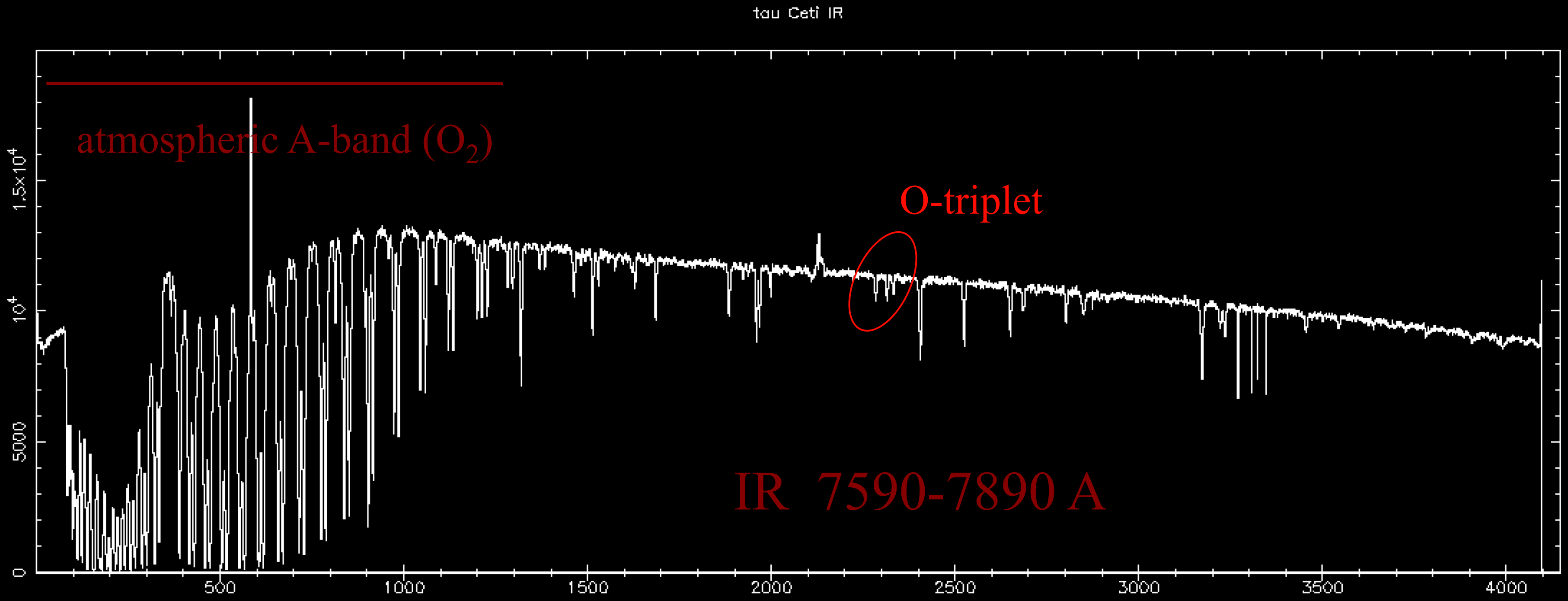


Green 5649-5873 A



Hα

Red 6481-6739 A



atmospheric A-band (O_2)

O-triplet

IR 7590-7890 A

GALAH Survey

- High resolution
  - R~28,000 SNR ~ 100 pe
- Large, diverse sample
  - All stars 12<V<14, δ<+10° , |b| targets
  - Galaxia: 75% thin disk, 24% thic
- Relatively bright stars
  - Comprehensive sample of th .

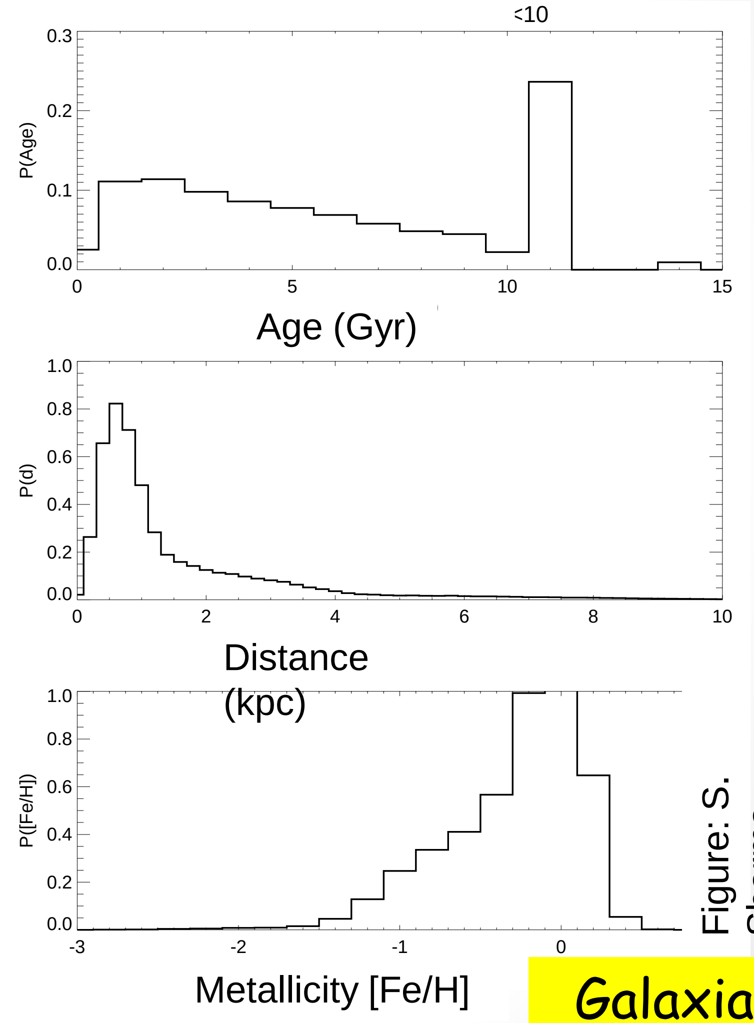
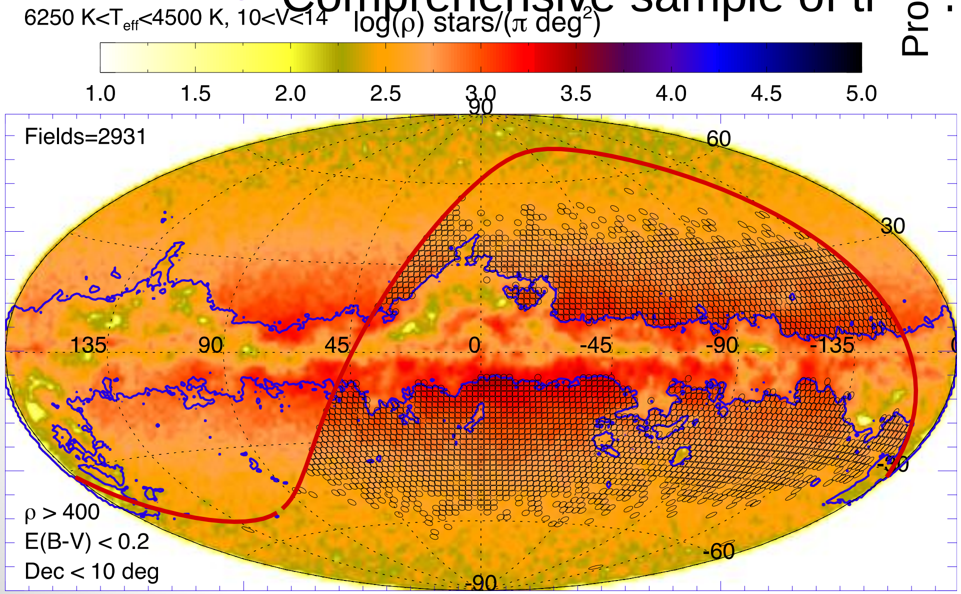
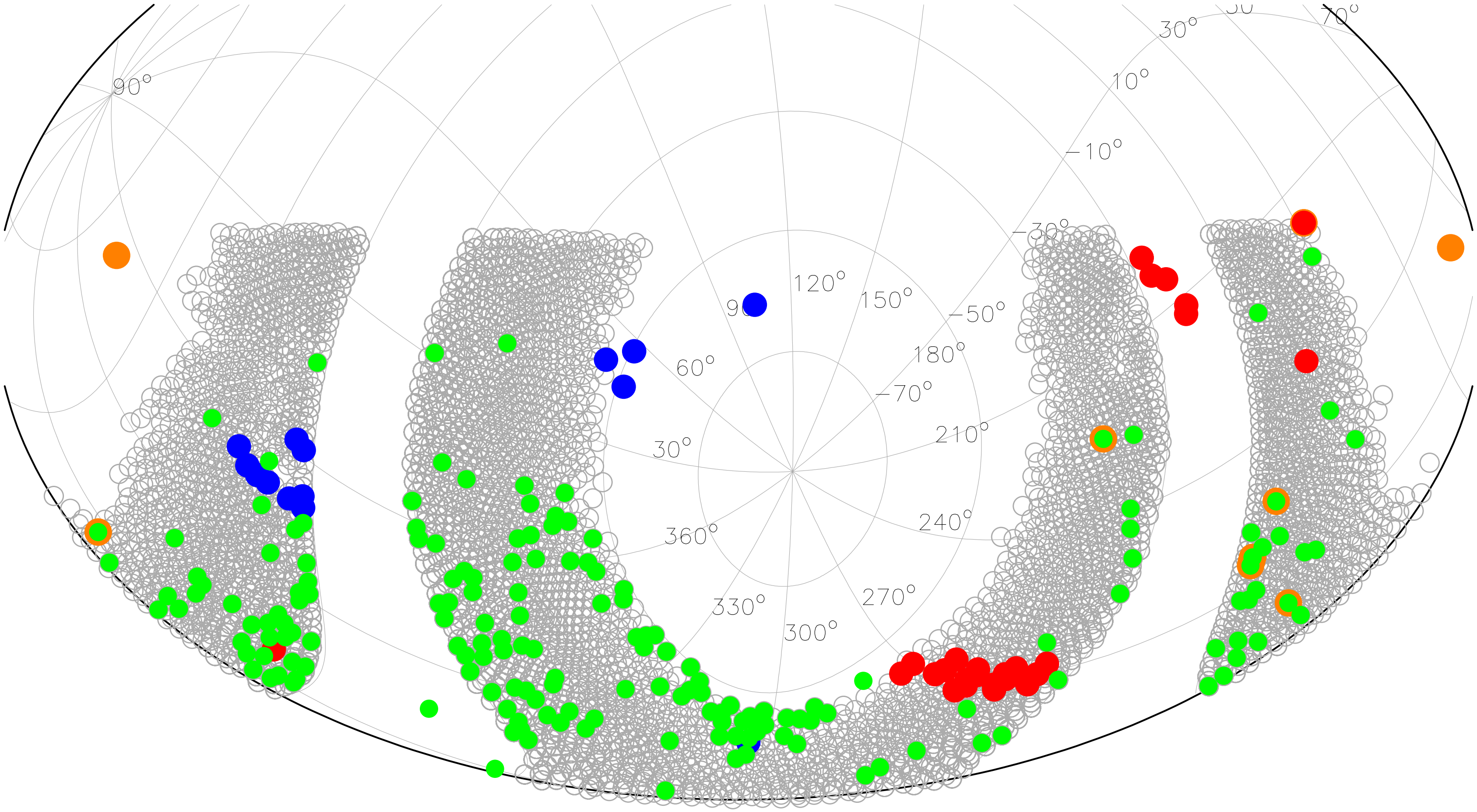


Figure: S. Sharma



Galaxia code

GALAH Survey – Year 1



- 🔴 Pilot survey (87% complete)
- 🟢 Regular survey
- 🔵 K2 field
- 🟠 Test field

Status on Nov. 4, 2014:
80,000+ stars
220 survey fields
97% through GAP pipeline

GALAH and Gaia

Gaia is a major element of the GALAH survey

Gaia (2014-19) will provide precision astrometry for $\sim 10^9$ stars

For V < 14, $\sigma_\pi = 10\ \mu\text{as}$, $\sigma_\mu = 10\ \mu\text{as yr}^{-1}$ **Gaia at its best !**

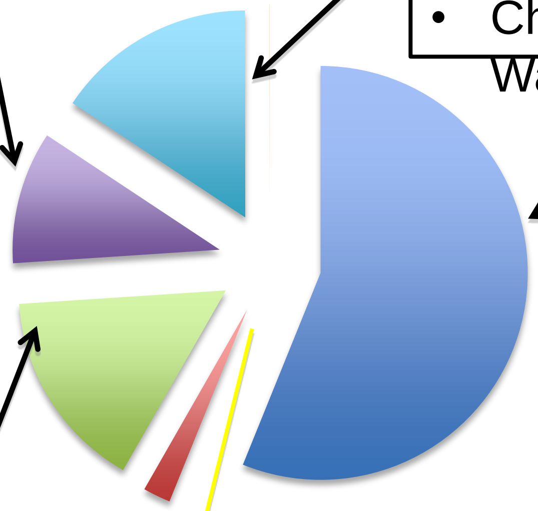
(1% distance errors at 1 kpc, 0.7 km s^{-1} velocity errors at 15 kpc)

⇒ accurate transverse velocities for all stars in GALAH
⇒ accurate distances for same
⇒ therefore accurate color-(absolute magnitude) diagram: independently check that "tagged" groups have common age

⇒ **major implications for stellar astrophysics <u>before</u> galactic archaeology,** e.g. correctness of 3D atmospheres, much improved abudance scale, seismic parameters, ages…

GALAH pilot survey projects

2016A data release



Survey targets

- 2095 stars, no color selection
- Chemical history of the Milky Way

Kepler-2 co-observing

- 1385 stars, color-selected
- Compare to asteroseismic log(g)
- Improve asteroseismic scaling relations

Thin vs thick disk

- 7503 stars, color-selected
- Normalisation between the two populations
- Separation in chemistry vs kinematics

CoRoT co-observing

- 2098 stars, no color selection
- Compare to asteroseismic log(g)
- Improve asteroseismic scaling relations

Cluster stars

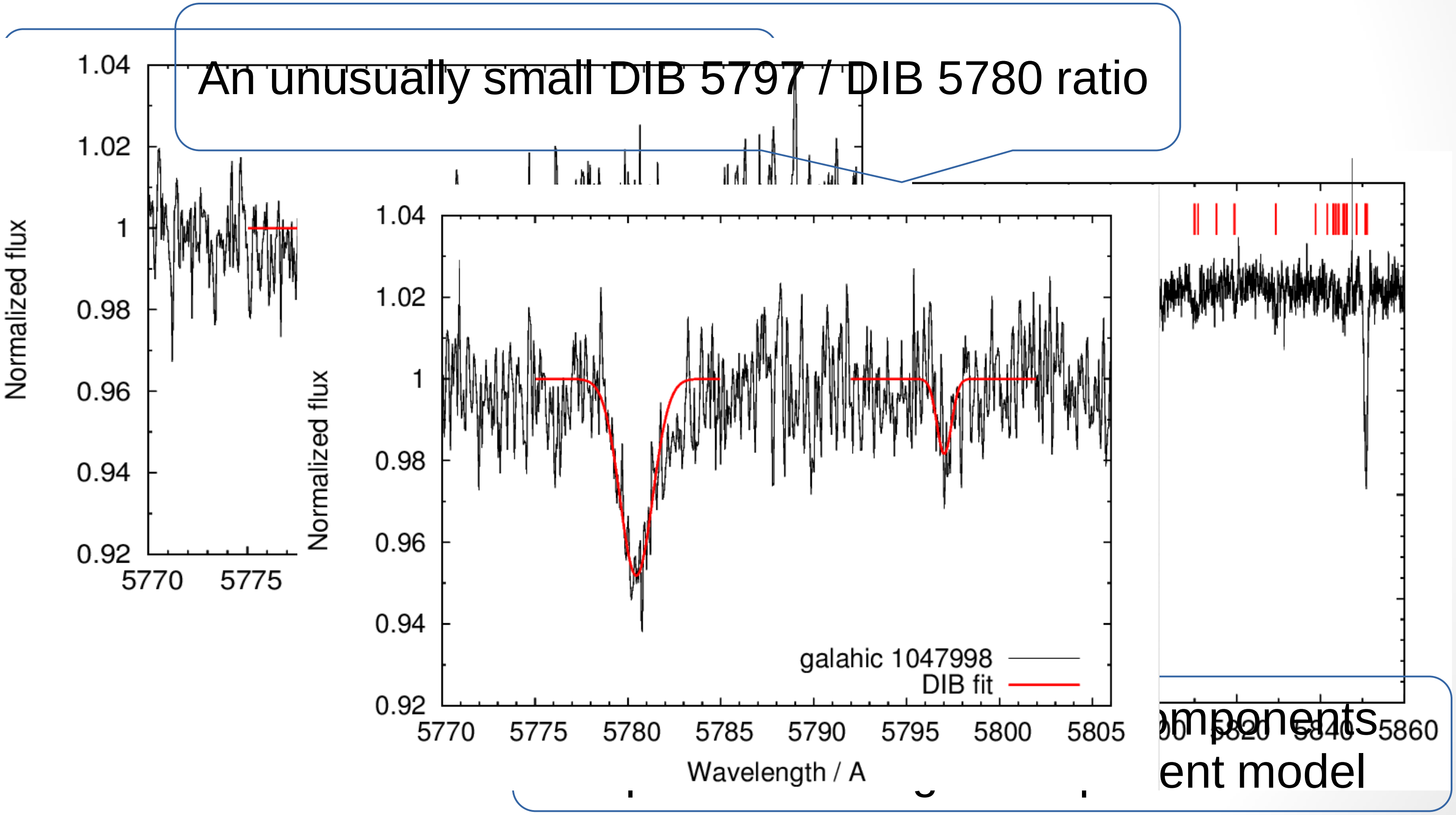
- 287 stars, carefully selected
- Pipeline verification
- Survey cross calibration

Exoplanet hosts

- 2 stars, serendipitous
- WASP transiting planets

Diffuse Interstellar Bands in GALAH Spectra

An unusually small DIB 5797 / DIB 5780 ratio



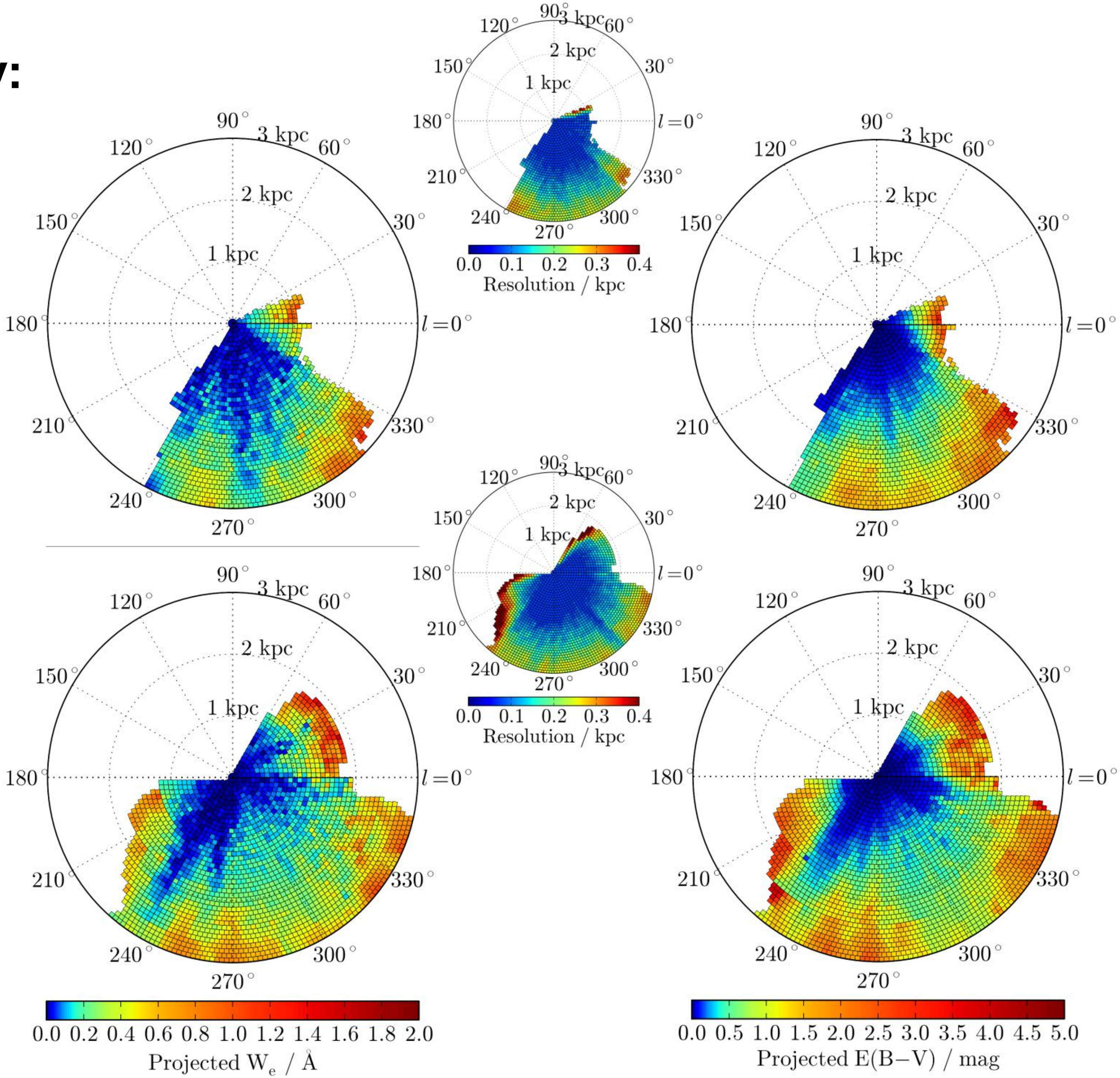
omponents

ent model

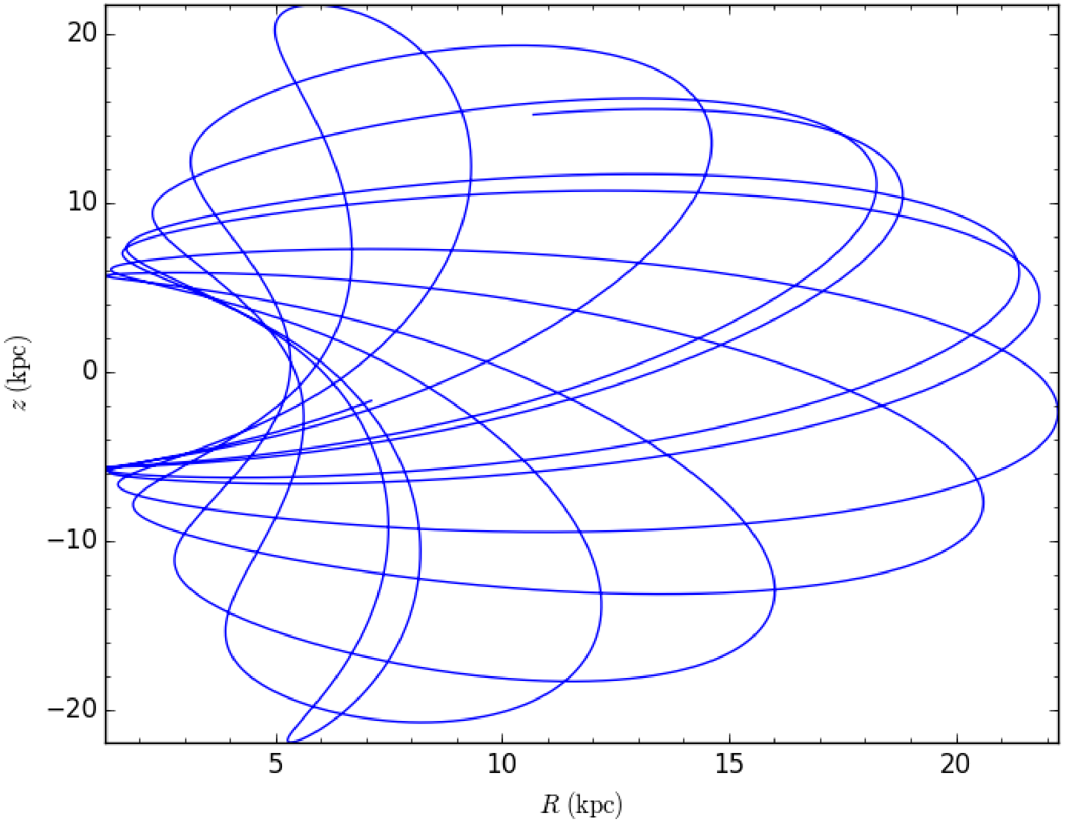
Zwitter, Kos et al. (Ljubljana)

RAVE survey:

DIB mapping of Galactic disk (Kos+ 2014)



High Velocity Stars in GALAH

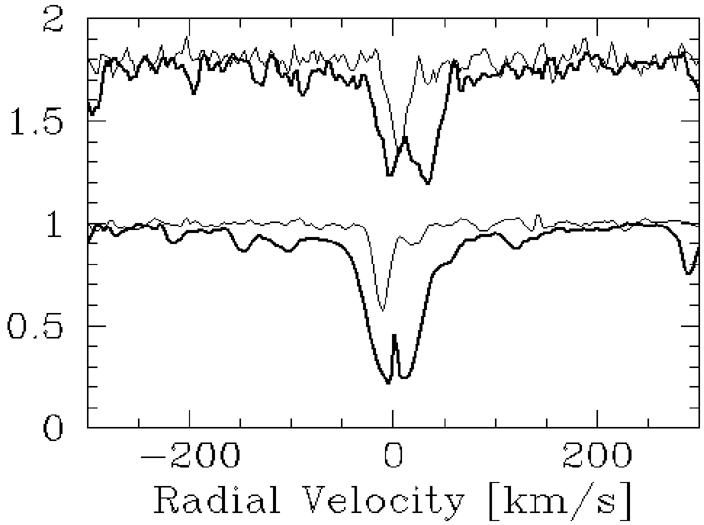


Preliminary orbit for NGC104-Lee3516 (heliocentric RV = 425 km s^{-1}; Norris, Freeman, DaCosta 1984)

- Preliminary orbital analyses suggest 8 of the 9 stars are bound

Schlesinger et al. (ANU)

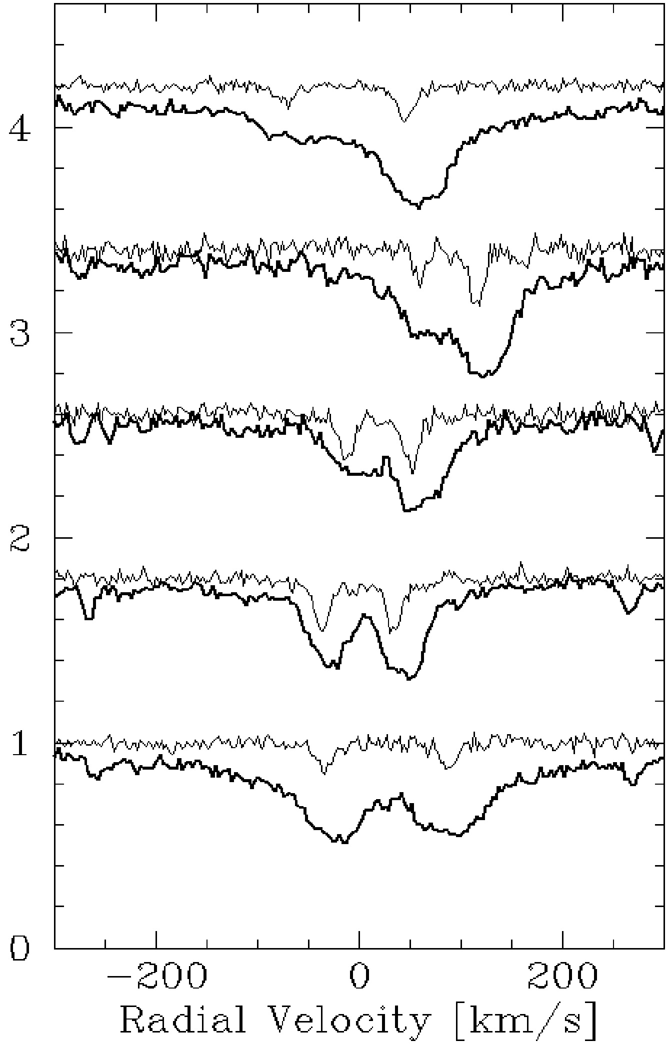
GALAH Stars with Peculiar Spectra



Objects with Hα emission component

Thick line: region around Hα
Thin line: region around He I 6678Å

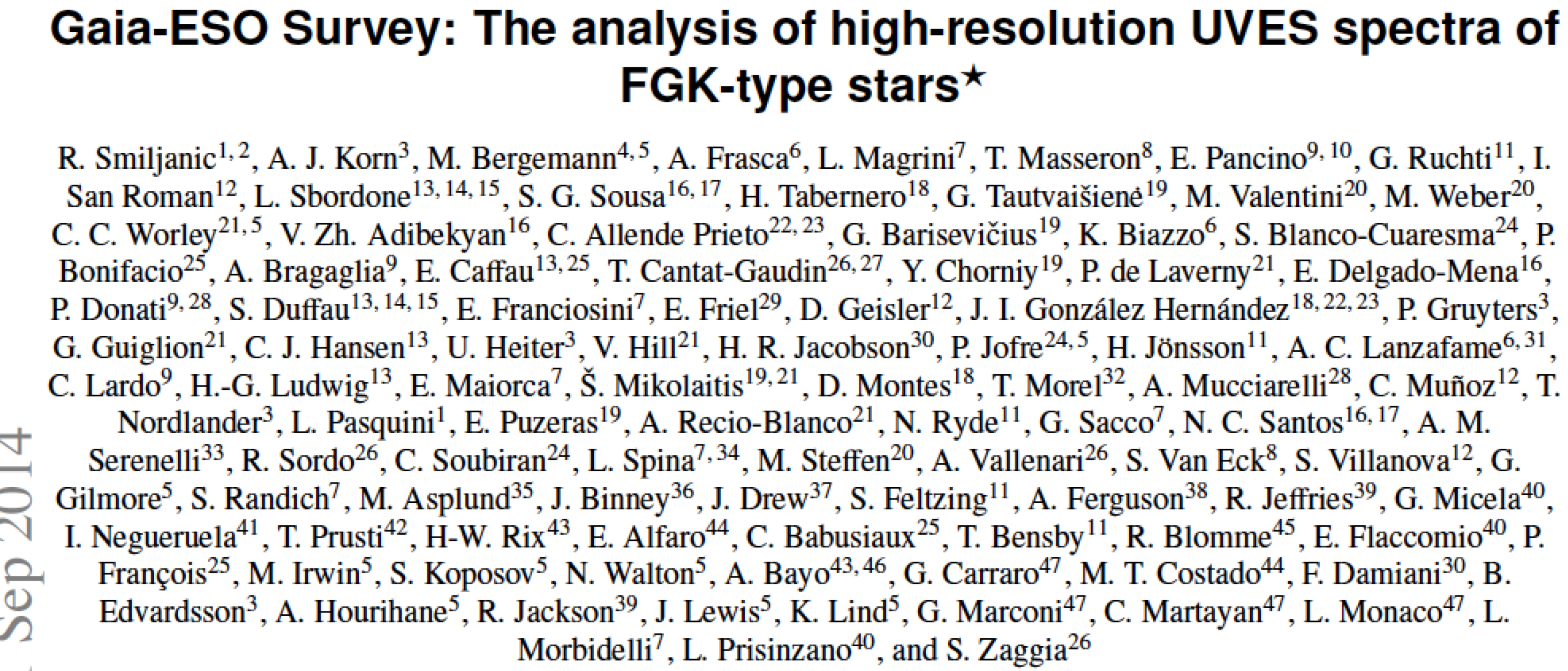
Double-lined spectroscopic binaries



Zwitter, Kos, Zerjal and Traven (Ljubljana)

Element abundances:

Early progress



Gaia-ESO Survey: The analysis of high-resolution UVES spectra of FGK-type stars[⋆]

R. Smiljanic[1,2], A. J. Korn[3], M. Bergemann[4,5], A. Frasca[6], L. Magrini[7], T. Masseron[8], E. Pancino[9,10], G. Ruchti[11], I. San Roman[12], L. Sbordone[13,14,15], S. G. Sousa[16,17], H. Tabernero[18], G. Tautvaišienė[19], M. Valentini[20], M. Weber[20], C. C. Worley[21,5], V. Zh. Adibekyan[16], C. Allende Prieto[22,23], G. Barisevičius[19], K. Biazzo[6], S. Blanco-Cuaresma[24], P. Bonifacio[25], A. Bragaglia[9], E. Caffau[13,25], T. Cantat-Gaudin[26,27], Y. Chorniy[19], P. de Laverny[21], E. Delgado-Mena[16], P. Donati[9,28], S. Duffau[13,14,15], E. Franciosini[7], E. Friel[29], D. Geisler[12], J. I. González Hernández[18,22,23], P. Gruyters[3], G. Guiglion[21], C. J. Hansen[13], U. Heiter[3], V. Hill[21], H. R. Jacobson[30], P. Jofre[24,5], H. Jönsson[11], A. C. Lanzafame[6,31], C. Lardo[9], H.-G. Ludwig[13], E. Maiorca[7], Š. Mikolaitis[19,21], D. Montes[18], T. Morel[32], A. Mucciarelli[28], C. Muñoz[12], T. Nordlander[3], L. Pasquini[1], E. Puzeras[19], A. Recio-Blanco[21], N. Ryde[11], G. Sacco[7], N. C. Santos[16,17], A. M. Serenelli[33], R. Sordo[26], C. Soubiran[24], L. Spina[7,34], M. Steffen[20], A. Vallenari[26], S. Van Eck[8], S. Villanova[12], G. Gilmore[5], S. Randich[7], M. Asplund[35], J. Binney[36], J. Drew[37], S. Feltzing[11], A. Ferguson[38], R. Jeffries[39], G. Micela[40], I. Negueruela[41], T. Prusti[42], H-W. Rix[43], E. Alfaro[44], C. Babusiaux[25], T. Bensby[11], R. Blomme[45], E. Flaccomio[40], P. François[25], M. Irwin[5], S. Koposov[5], N. Walton[5], A. Bayo[43,46], G. Carraro[47], M. T. Costado[44], F. Damiani[30], B. Edvardsson[3], A. Hourihane[5], R. Jackson[39], J. Lewis[5], K. Lind[5], G. Marconi[47], C. Martayan[47], L. Monaco[47], L. Morbidelli[7], L. Prisinzano[40], and S. Zaggia[26]

ABUNDANCES, STELLAR PARAMETERS, AND SPECTRA FROM THE SDSS-III/APOGEE SURVEY

Jon A. Holtzman[1], Matthew Shetrone [2], Jennifer A. Johnson[3], Carlos Allende Prieto[4,5], Friedrich Anders[6,7], Brett Andrews[8], Timothy C. Beers[9], Dmitry Bizyaev [10], Michael R. Blanton[11], Jo Bovy[12,13], Ricardo Carrera[4], Katia Cunha[14,15], Daniel J. Eisenstein[17], Diane Feuillet[1], Peter M. Frinchaboy[17], Jessica Galbraith-Frew[18], Ana E. García Pérez[4], D. Anibal García Hernández[4], Sten Hasselquist[1], Michael R. Hayden[1], Fred R. Hearty[19], Inese Ivans[18], Steven R. Majewski[20], Sarah Martell[21], Szabolcs Meszaros[22], Demitri Muna[3], David Nidever[23], Duy Cuong Nguyen[24], Robert W. O'Connell[20], Kaike Pan[10], Marc Pinsonneault[3], Annie C. Robin[25], Ricardo P. Schiavon[26], Neville Shane[20], Jennifer Sobeck[20], Verne V. Smith[14], Nicholas Troup[20], David H. Weinberg[3], John C. Wilson[20], W. M. Wood-Vasey[8], Olga Zamora[4], Gail Zasowski[27]

Draft version January 20, 2015

First test: *GAP reduction pipeline* ➔ abundance calibration

Observe twilight in 400 fibres

Do spectra have solar abundances?

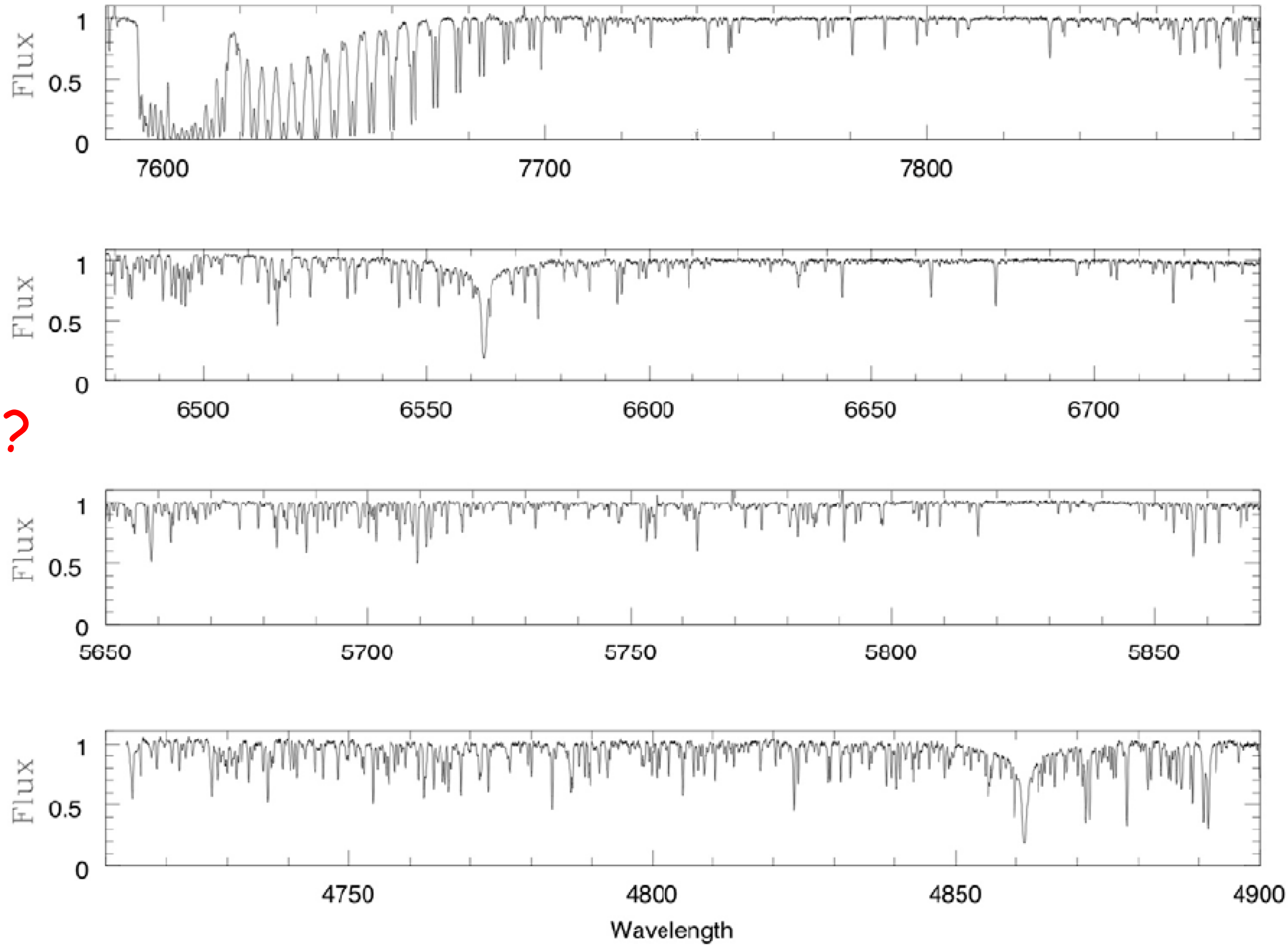


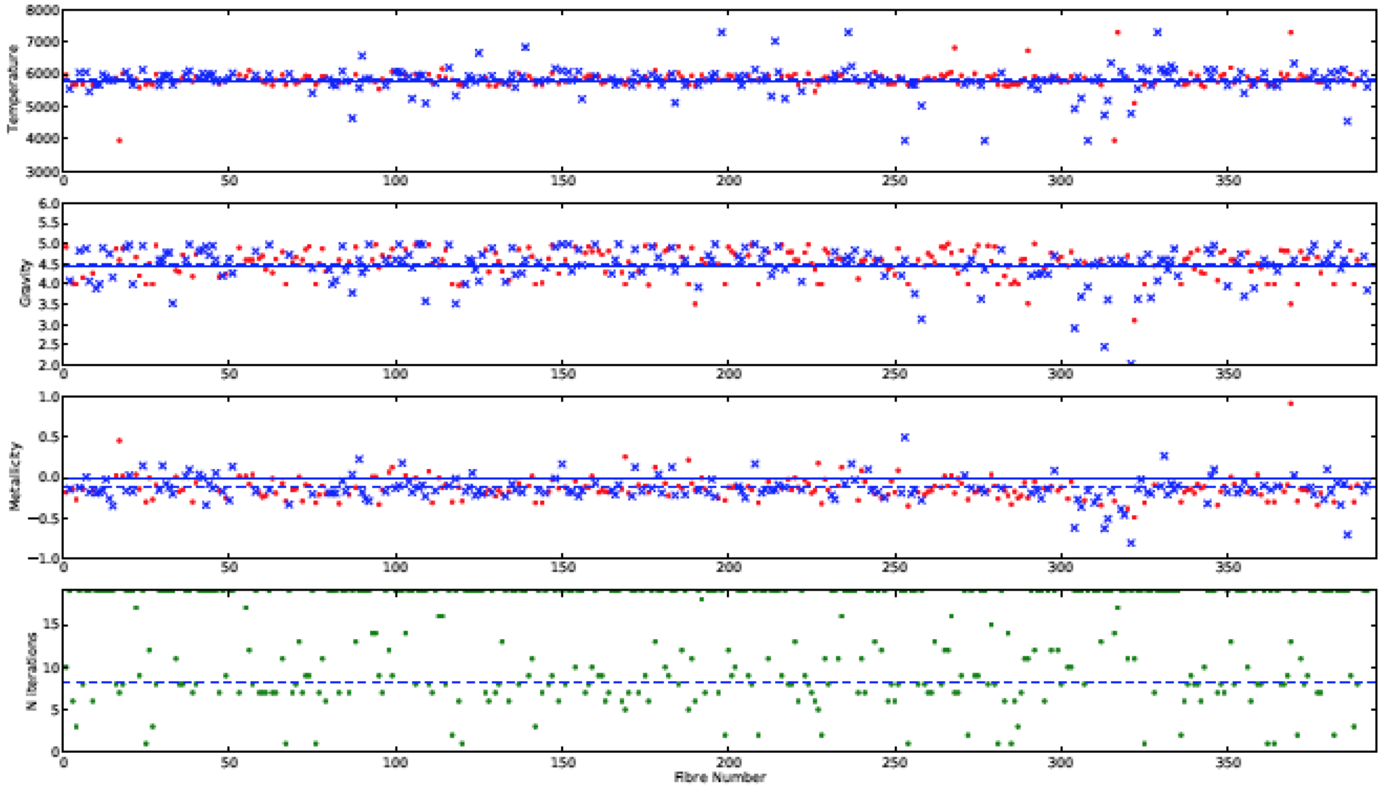
Figure 26. shows the extracted and normalized solar spectra from the four HERMES channels

er the 209 converged
were $T_{eff} = 5837K$,
pted $T_{eff} = 5780K$,
$_{eff} = +57K$, Δ logg
$= 0.04$ and $\Delta[Fe/H] = -0.11$dex.

First test: grabbed from internal report

Twilight, 400 fibres

Wylie de Boer (Lead), Sneden, d'Orazi

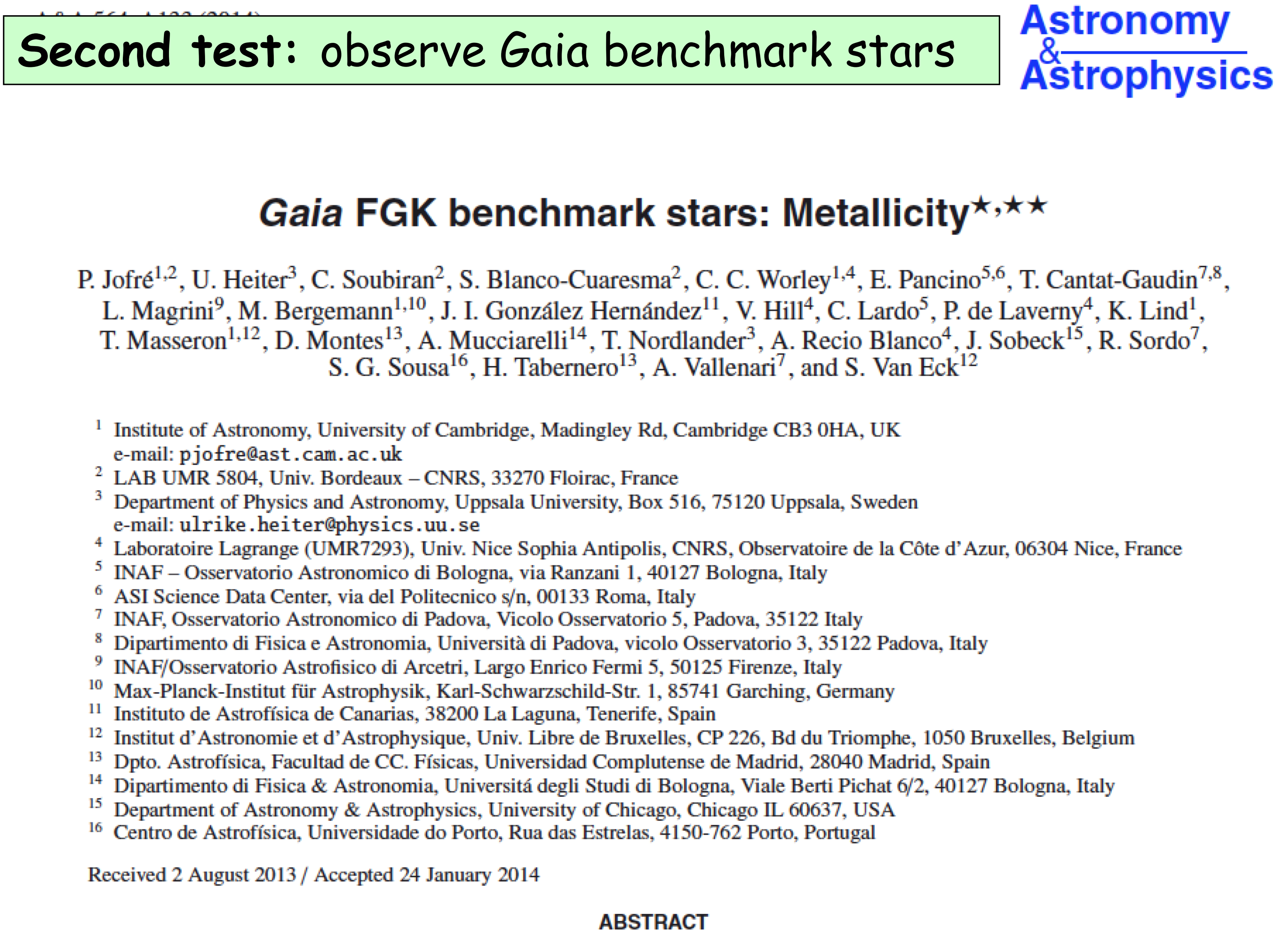


Theremin/MOOG

Blue dots – not converged

Figure 5: Stellar parameters from Theremin output as a function of fiber number.

Second test: observe Gaia benchmark stars



Astronomy & Astrophysics

Gaia FGK benchmark stars: Metallicity★,★★

P. Jofré[1,2], U. Heiter[3], C. Soubiran[2], S. Blanco-Cuaresma[2], C. C. Worley[1,4], E. Pancino[5,6], T. Cantat-Gaudin[7,8], L. Magrini[9], M. Bergemann[1,10], J. I. González Hernández[11], V. Hill[4], C. Lardo[5], P. de Laverny[4], K. Lind[1], T. Masseron[1,12], D. Montes[13], A. Mucciarelli[14], T. Nordlander[3], A. Recio Blanco[4], J. Sobeck[15], R. Sordo[7], S. G. Sousa[16], H. Tabernero[13], A. Vallenari[7], and S. Van Eck[12]

[1] Institute of Astronomy, University of Cambridge, Madingley Rd, Cambridge CB3 0HA, UK
e-mail: `pjofre@ast.cam.ac.uk`
[2] LAB UMR 5804, Univ. Bordeaux – CNRS, 33270 Floirac, France
[3] Department of Physics and Astronomy, Uppsala University, Box 516, 75120 Uppsala, Sweden
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[4] Laboratoire Lagrange (UMR7293), Univ. Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur, 06304 Nice, France
[5] INAF – Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy
[6] ASI Science Data Center, via del Politecnico s/n, 00133 Roma, Italy
[7] INAF, Osservatorio Astronomico di Padova, Vicolo Osservatorio 5, Padova, 35122 Italy
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[9] INAF/Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125 Firenze, Italy
[10] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany
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[12] Institut d'Astronomie et d'Astrophysique, Univ. Libre de Bruxelles, CP 226, Bd du Triomphe, 1050 Bruxelles, Belgium
[13] Dpto. Astrofísica, Facultad de CC. Físicas, Universidad Complutense de Madrid, 28040 Madrid, Spain
[14] Dipartimento di Fisica & Astronomia, Universitá degli Studi di Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy
[15] Department of Astronomy & Astrophysics, University of Chicago, Chicago IL 60637, USA
[16] Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal

Received 2 August 2013 / Accepted 24 January 2014

ABSTRACT

Second test

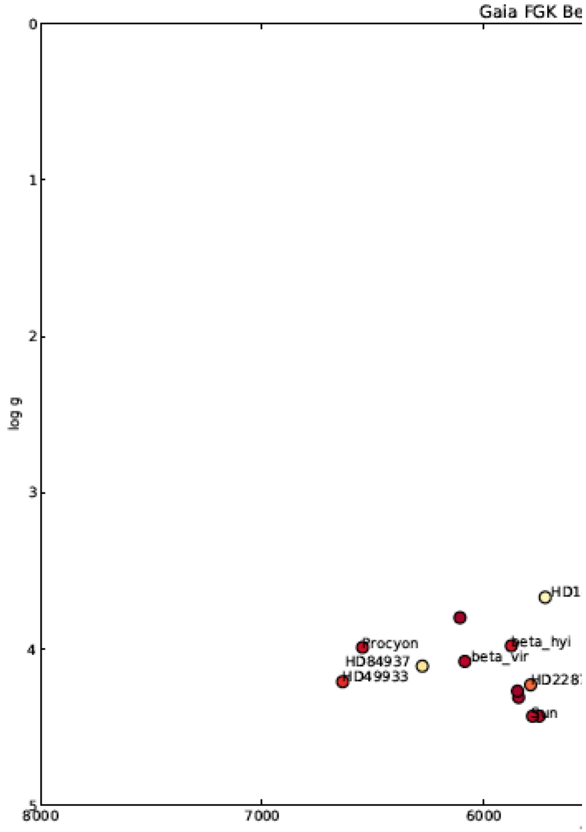


Figure 1: HR diagram of the 34
The 18 benchmark stars successfull
shading is a measure of metallicity,

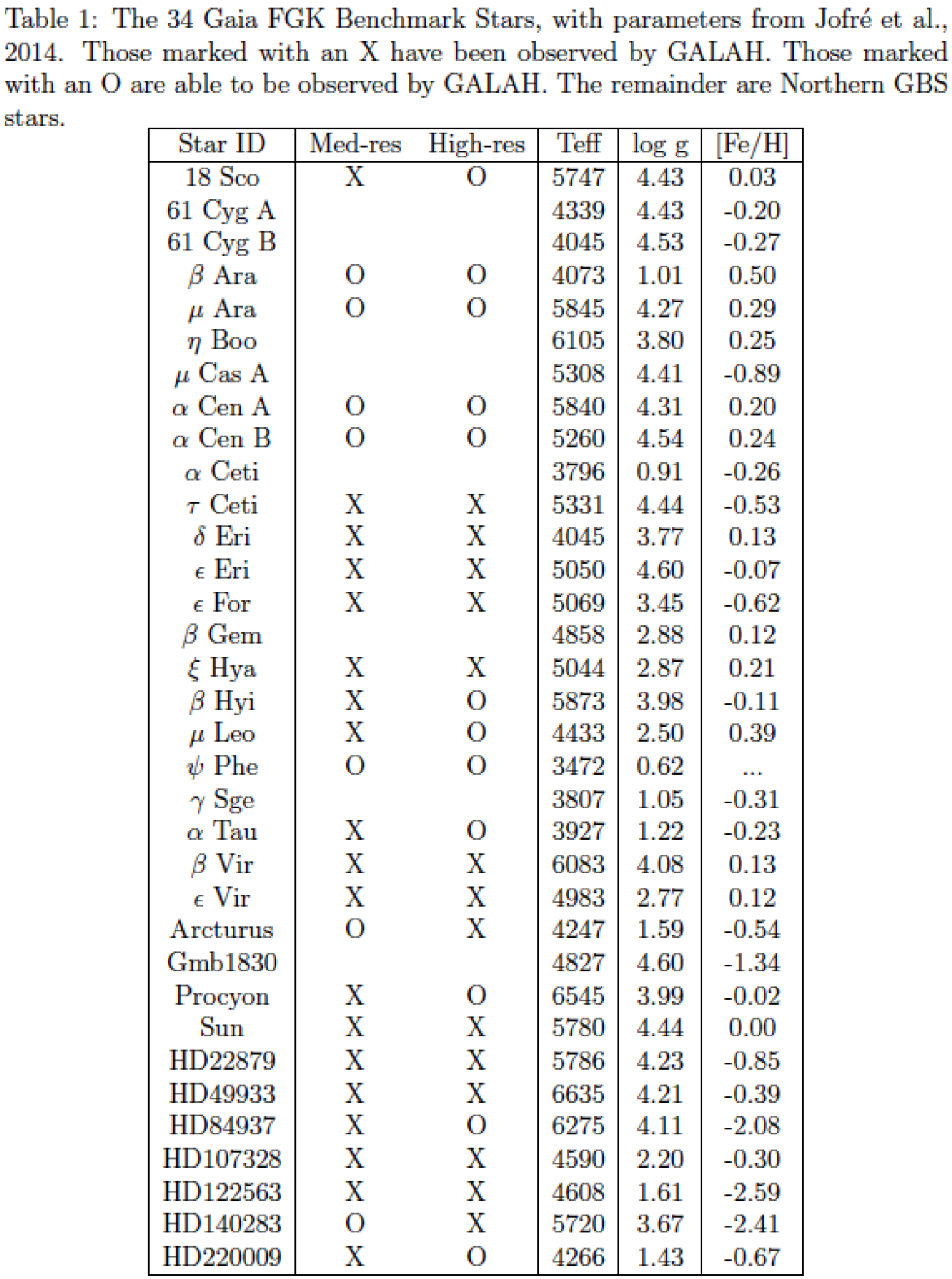


Table 1: The 34 Gaia FGK Benchmark Stars, with parameters from Jofré et al., 2014. Those marked with an X have been observed by GALAH. Those marked with an O are able to be observed by GALAH. The remainder are Northern GBS stars.

Star ID	Med-res	High-res	Teff	log g	[Fe/H]
18 Sco	X	O	5747	4.43	0.03
61 Cyg A			4339	4.43	-0.20
61 Cyg B			4045	4.53	-0.27
β Ara	O	O	4073	1.01	0.50
μ Ara	O	O	5845	4.27	0.29
η Boo			6105	3.80	0.25
μ Cas A			5308	4.41	-0.89
α Cen A	O	O	5840	4.31	0.20
α Cen B	O	O	5260	4.54	0.24
α Ceti			3796	0.91	-0.26
τ Ceti	X	X	5331	4.44	-0.53
δ Eri	X	X	4045	3.77	0.13
ϵ Eri	X	X	5050	4.60	-0.07
ϵ For	X	X	5069	3.45	-0.62
β Gem			4858	2.88	0.12
ξ Hya	X	X	5044	2.87	0.21
β Hyi	X	O	5873	3.98	-0.11
μ Leo	X	O	4433	2.50	0.39
ψ Phe	O	O	3472	0.62	...
γ Sge			3807	1.05	-0.31
α Tau	X	O	3927	1.22	-0.23
β Vir	X	X	6083	4.08	0.13
ϵ Vir	X	X	4983	2.77	0.12
Arcturus	O	X	4247	1.59	-0.54
Gmb1830			4827	4.60	-1.34
Procyon	X	O	6545	3.99	-0.02
Sun	X	X	5780	4.44	0.00
HD22879	X	X	5786	4.23	-0.85
HD49933	X	X	6635	4.21	-0.39
HD84937	X	O	6275	4.11	-2.08
HD107328	X	X	4590	2.20	-0.30
HD122563	X	X	4608	1.61	-2.59
HD140283	O	X	5720	3.67	-2.41
HD220009	X	O	4266	1.43	-0.67

Second test

☐ Jofre table values
☐ No initial conditions
} scatter same

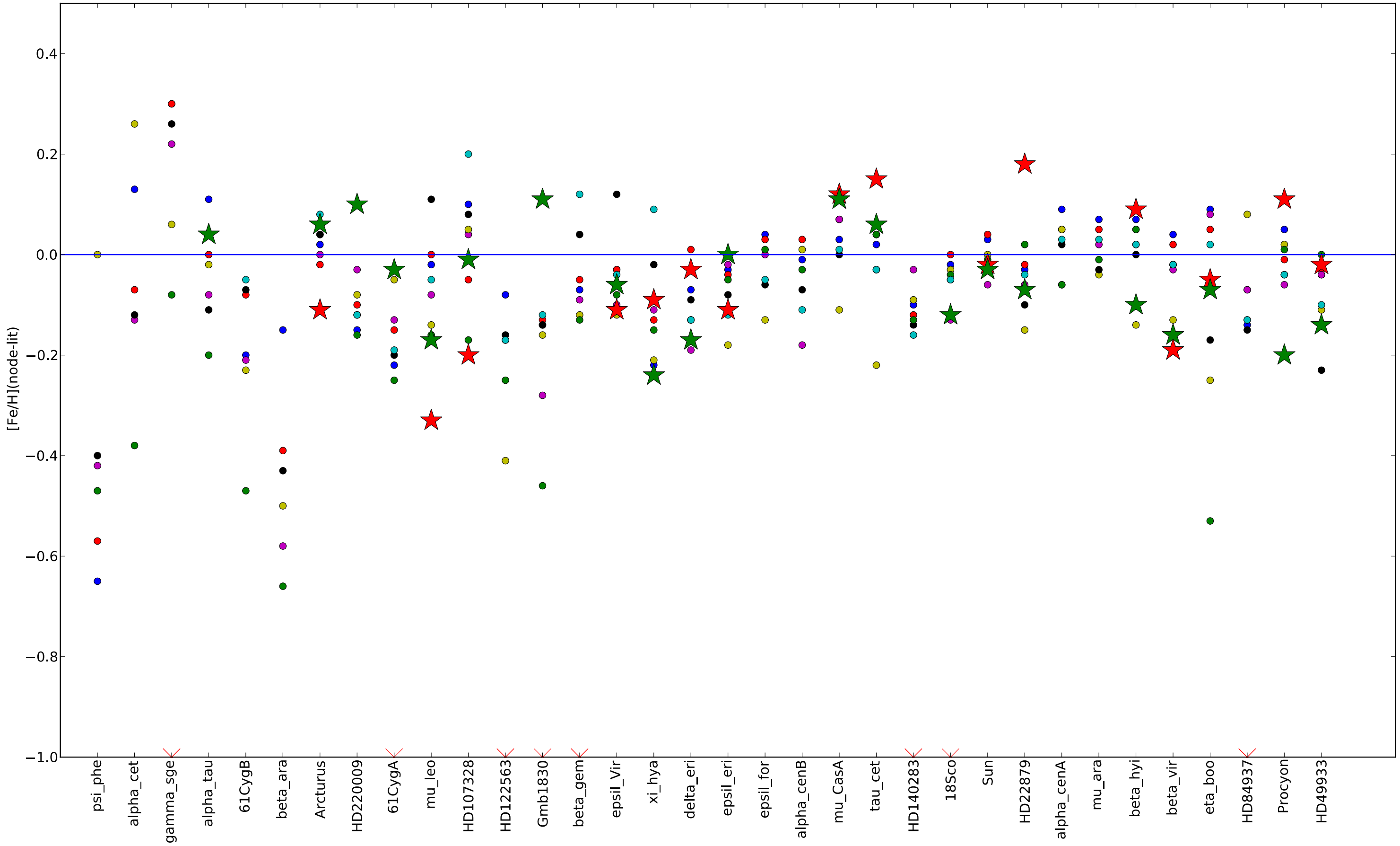


Figure 2: Accepted stellar parameters vs those derived by Theremin for 15 GALAH-observed GBS stars and the Sun (as observed by UVES).

Next step - 3D atmospheres (Asplund, Bergemann)

Kepler fields:

K1 fields: Sharma, Stello, JBH (2015) – many problems

K2 fields: Sharma, Stello, Huber (Kepler GA led by USyd)

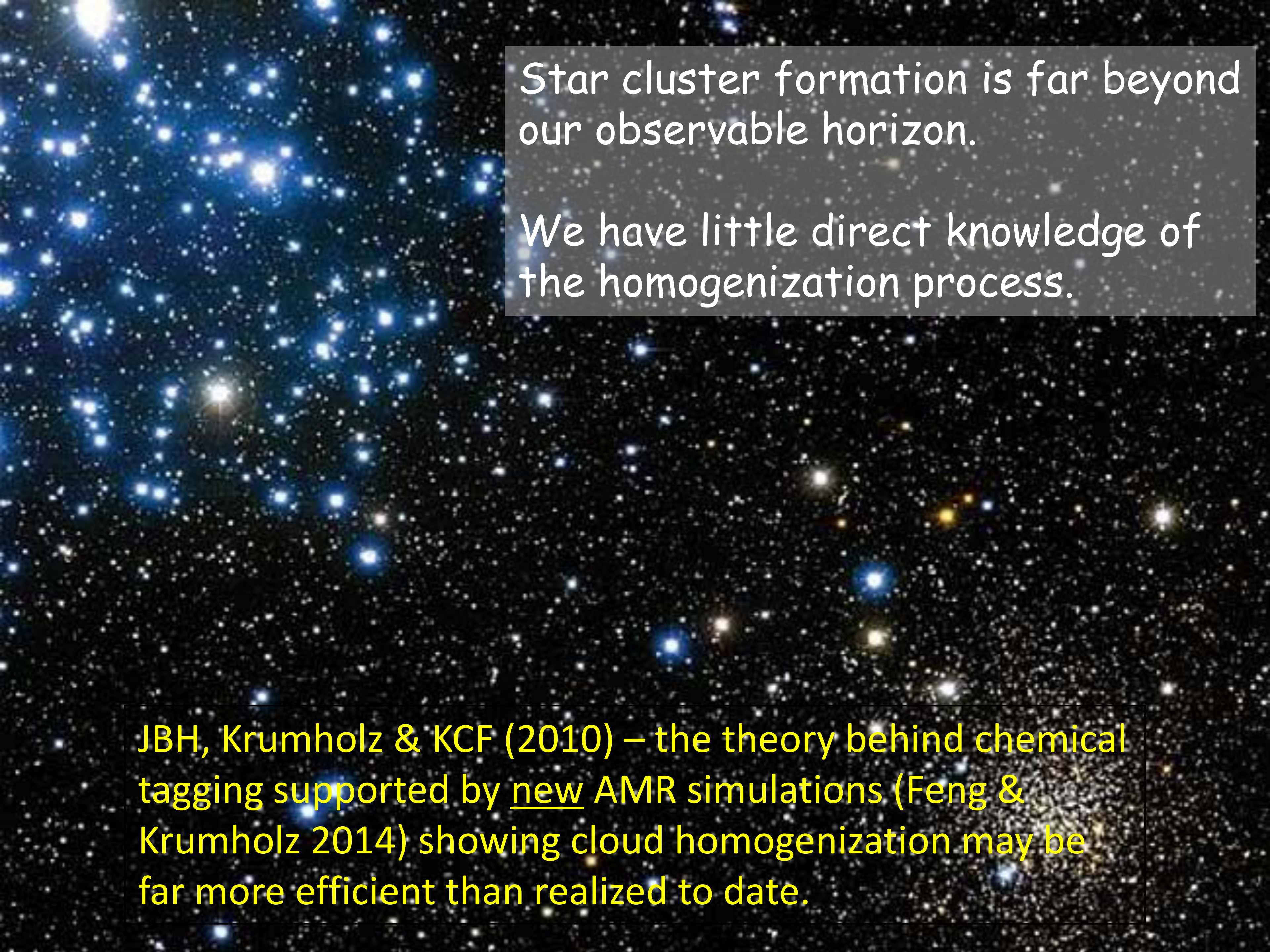
- New postdoc position for **model builder** or **asteroseismologist**.
- Contact jbh@physics.usyd.edu.au or bedding@physics.usyd.edu.au

Kepler fields: GALAH observations

- Field **0**: 0% - 400 stars, low quality K2 data
- Field **1**: 0% - low density (V~15) need dark time!
- Field **2**: 100% done
- Field **3**: 80% done
- Field **4, 5**: scheduled to observe

Galactic archaeology:

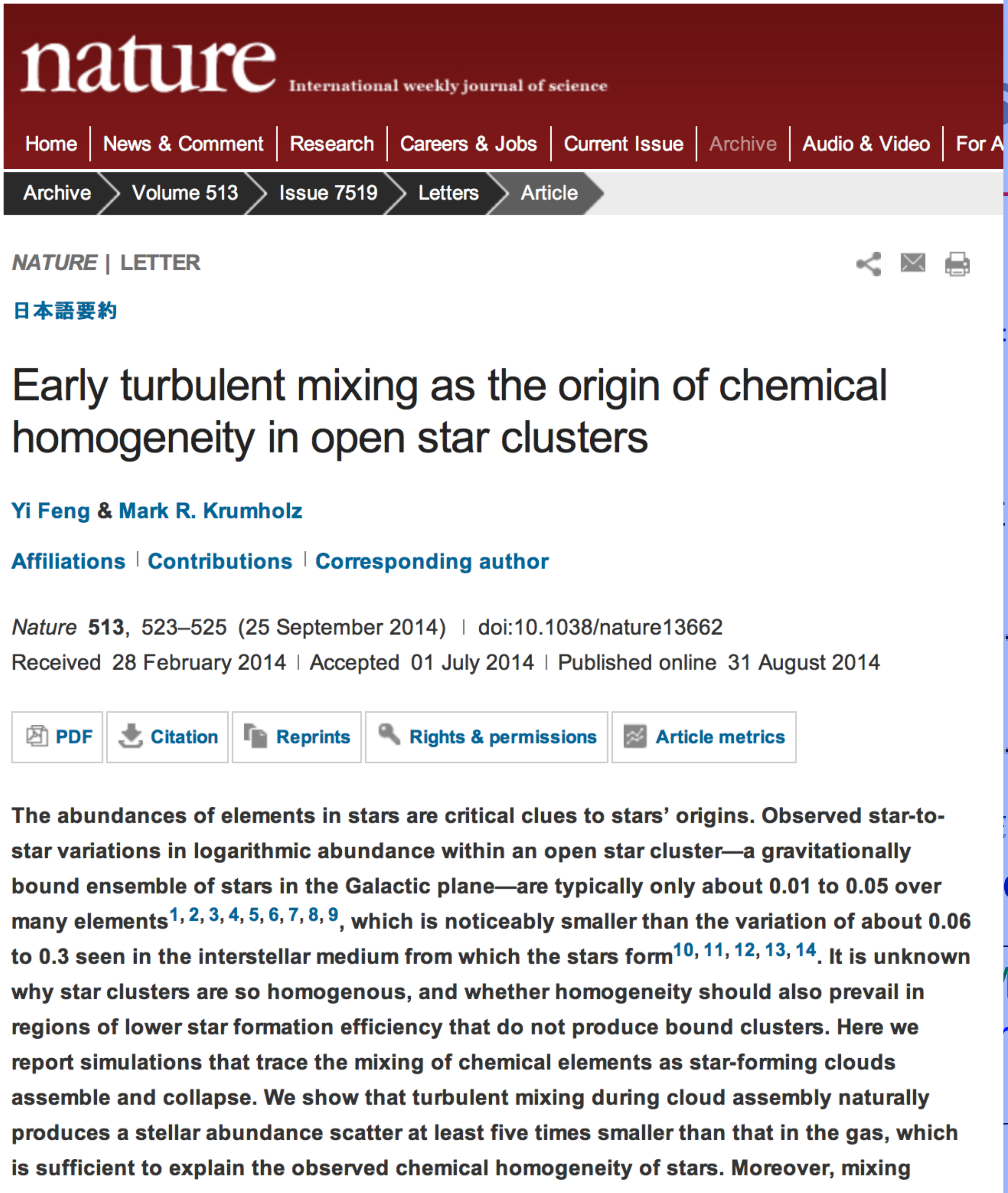
Fossil recovery by chemical tagging



Star cluster formation is far beyond our observable horizon.

We have little direct knowledge of the homogenization process.

JBH, Krumholz & KCF (2010) – the theory behind chemical tagging supported by new AMR simulations (Feng & Krumholz 2014) showing cloud homogenization may be far more efficient than realized to date.



NATURE | LETTER

日本語要約

Early turbulent mixing as the origin of chemical homogeneity in open star clusters

Yi Feng & Mark R. Krumholz

Affiliations | Contributions | Corresponding author

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The abundances of elements in stars are critical clues to stars' origins. Observed star-to-star variations in logarithmic abundance within an open star cluster—a gravitationally bound ensemble of stars in the Galactic plane—are typically only about 0.01 to 0.05 over many elements[1, 2, 3, 4, 5, 6, 7, 8, 9], which is noticeably smaller than the variation of about 0.06 to 0.3 seen in the interstellar medium from which the stars form[10, 11, 12, 13, 14]. It is unknown why star clusters are so homogenous, and whether homogeneity should also prevail in regions of lower star formation efficiency that do not produce bound clusters. Here we report simulations that trace the mixing of chemical elements as star-forming clouds assemble and collapse. We show that turbulent mixing during cloud assembly naturally produces a stellar abundance scatter at least five times smaller than that in the gas, which is sufficient to explain the observed chemical homogeneity of stars. Moreover, mixing

tar cluster?

, MRK, KCF (2010)

cloud gas mass ~ 10^6 M_o

cloud col. density ~ 0.3 g cm^{-2}

io of kinetic to gravitational

$$\Big)^{1/4} \mathrm{Myr}$$

$$= M_*/M = 0.2$$

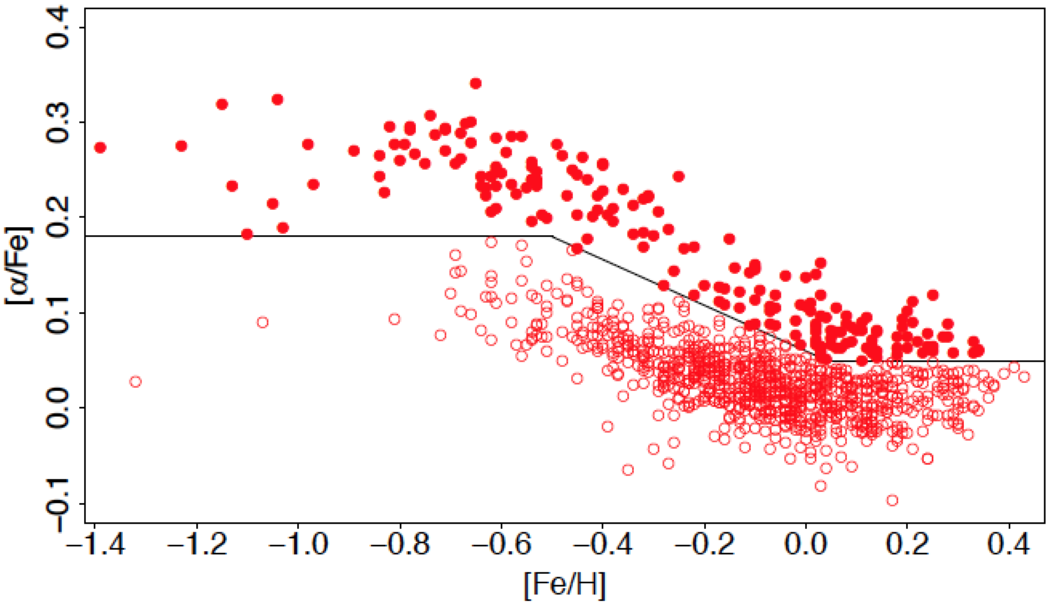
e. fraction of cloud ➔ stars

$_o$ are uniform since

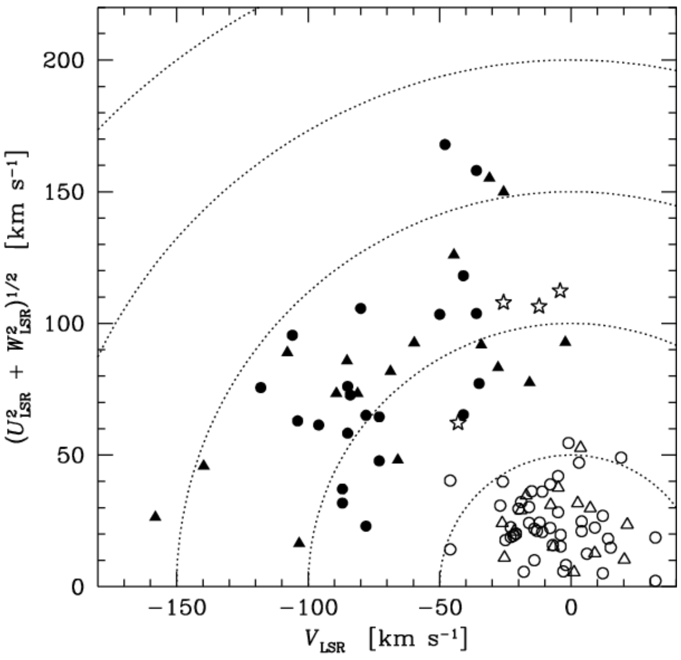
globular densities,

Overview

We know the thick disk is ancient with a distinct chemical and kinematic signature, at least for the most part.



Haywood+13

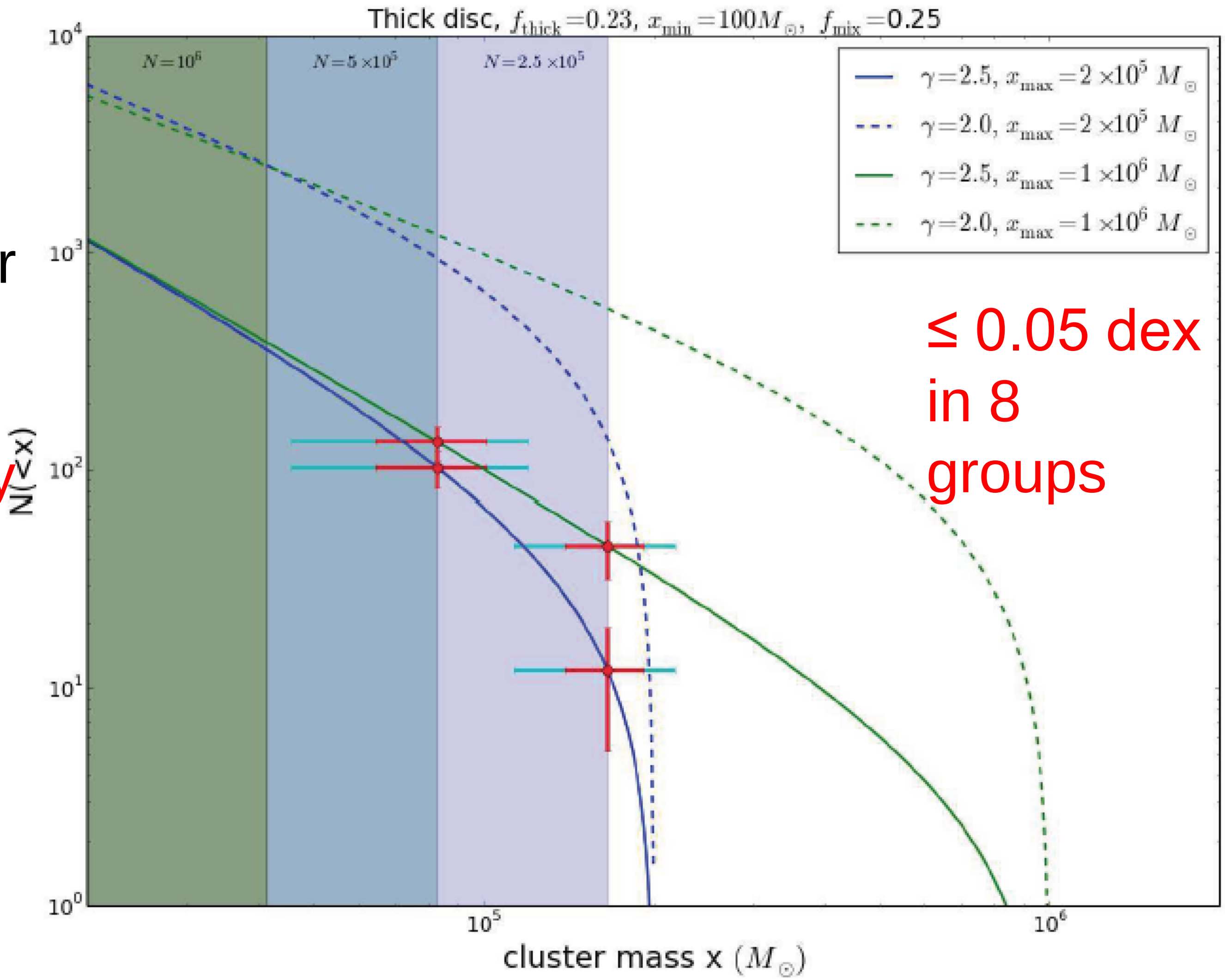


Bensby+12

Thick disk enhanced α/Fe is excellent news for chemical tagging.

(Bovy tells us fully half of the disk !)

Impulsive SF forms the largest star clusters and drives us to high α/Fe.



≤ 0.05 dex in 8 groups

Fig. 1: The number of clusters recovered from a simulated GALAH survey, as a function of cluster mass. Dependences on star formation parameters and implications for survey size are explained in the text.

JBH+ (2010)

Summary

- Star cluster formation lies beyond our observable horizon.
- Chemically tagging just a few systems will teach us a great deal about migration.
- If strong migration is real, *in situ* information is scrambled, thus detailed chemistry via GALAH is essential to progress.
- Reconstructing star clusters is necessary to relate cluster age distributions to cluster formation history.
- Reconstructed CMFs and alpha/Fe distributions will tell us about major vs. minor mergers (vs. migration) with cosmic time.