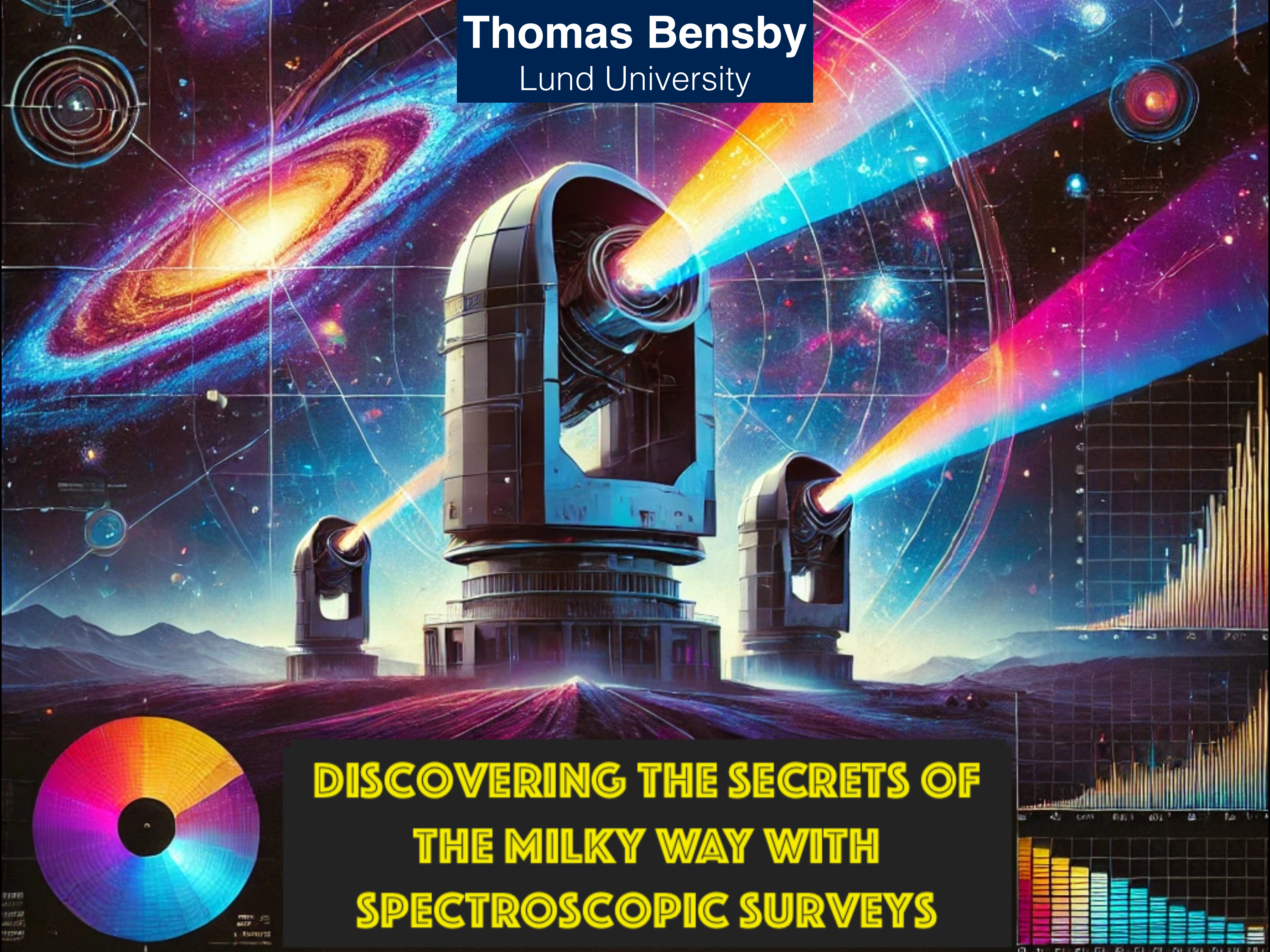
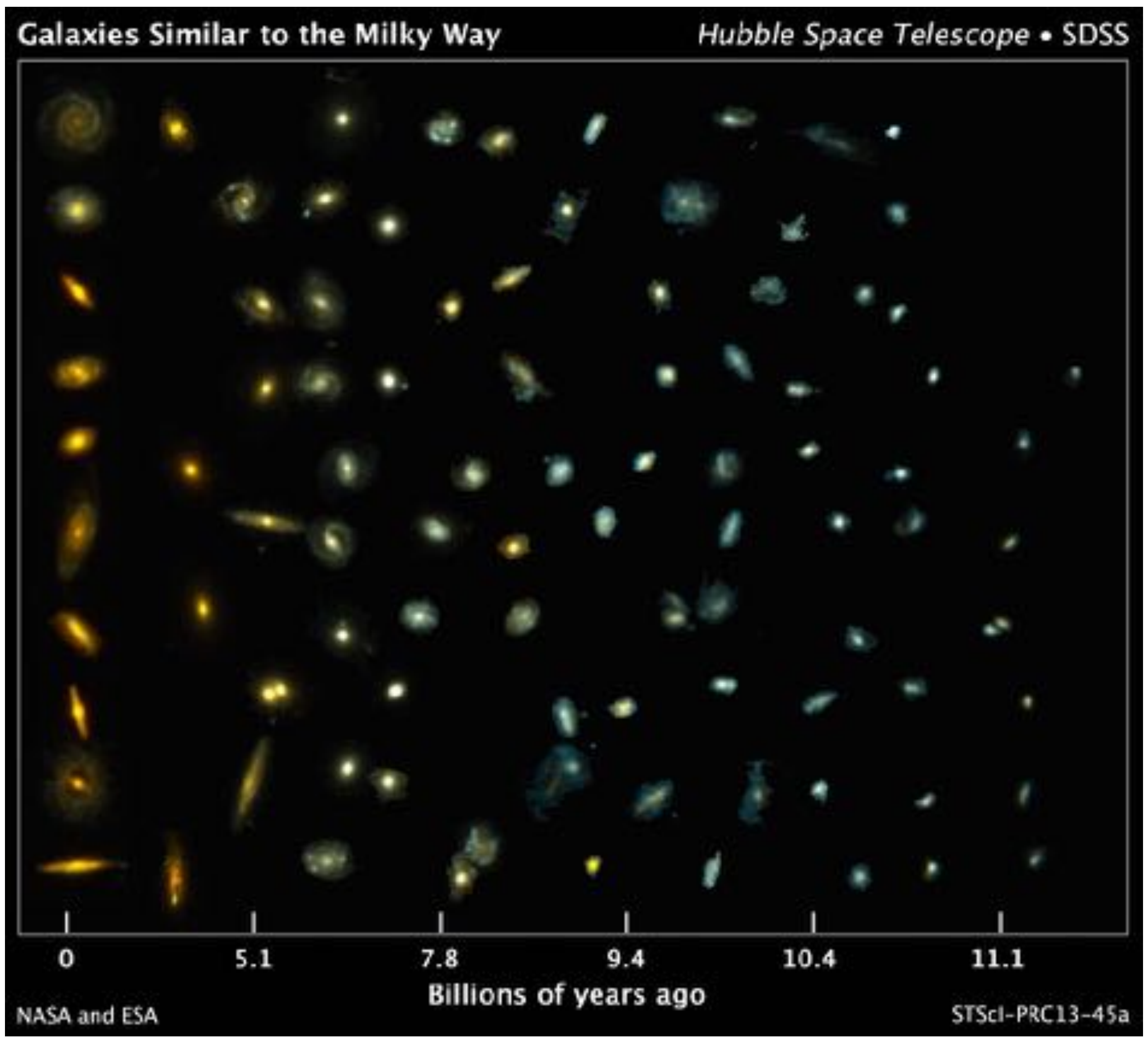
Thomas Bensby
Lund University



DISCOVERING THE SECRETS OF THE MILKY WAY WITH SPECTROSCOPIC SURVEYS

One Big Question in Astrophysics

How did these blobs become nice spiral galaxies?



Looking back in time

?

Present-day spirals

The Milky Way

The way we knew it for a long time.....

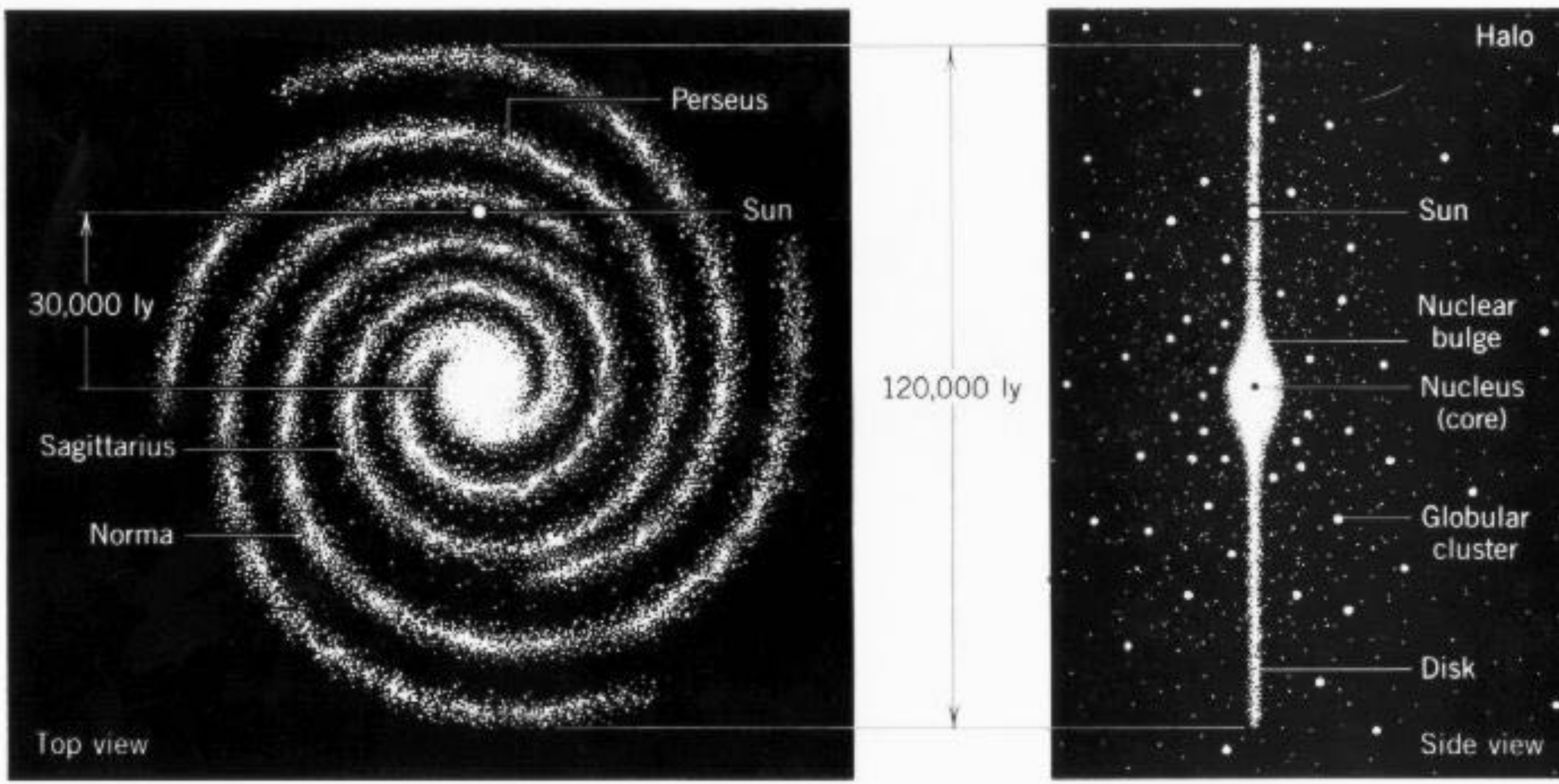
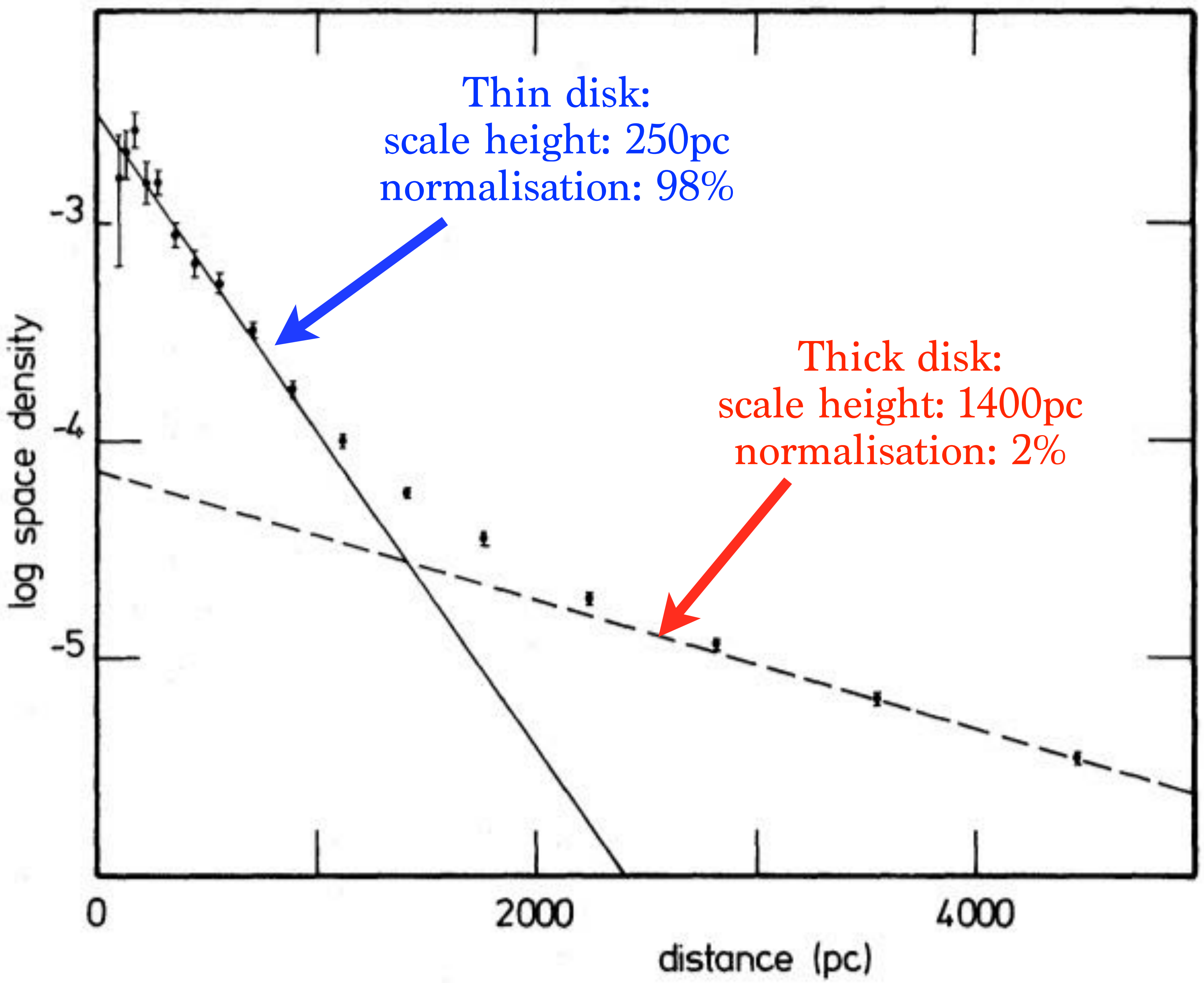


Image: John Wiley and Sons Inc.

The Galactic disks

There are actually two!



(Gilmore & Reid, 1983, MNRAS, 202, 102)

- Star counts toward the Galactic South Pole
- Stellar density not matched by one exponential, two needed
- **Thin** and **thick** disks
- Differs in terms of:
  - Kinematics
  - Chemical composition
  - Ages

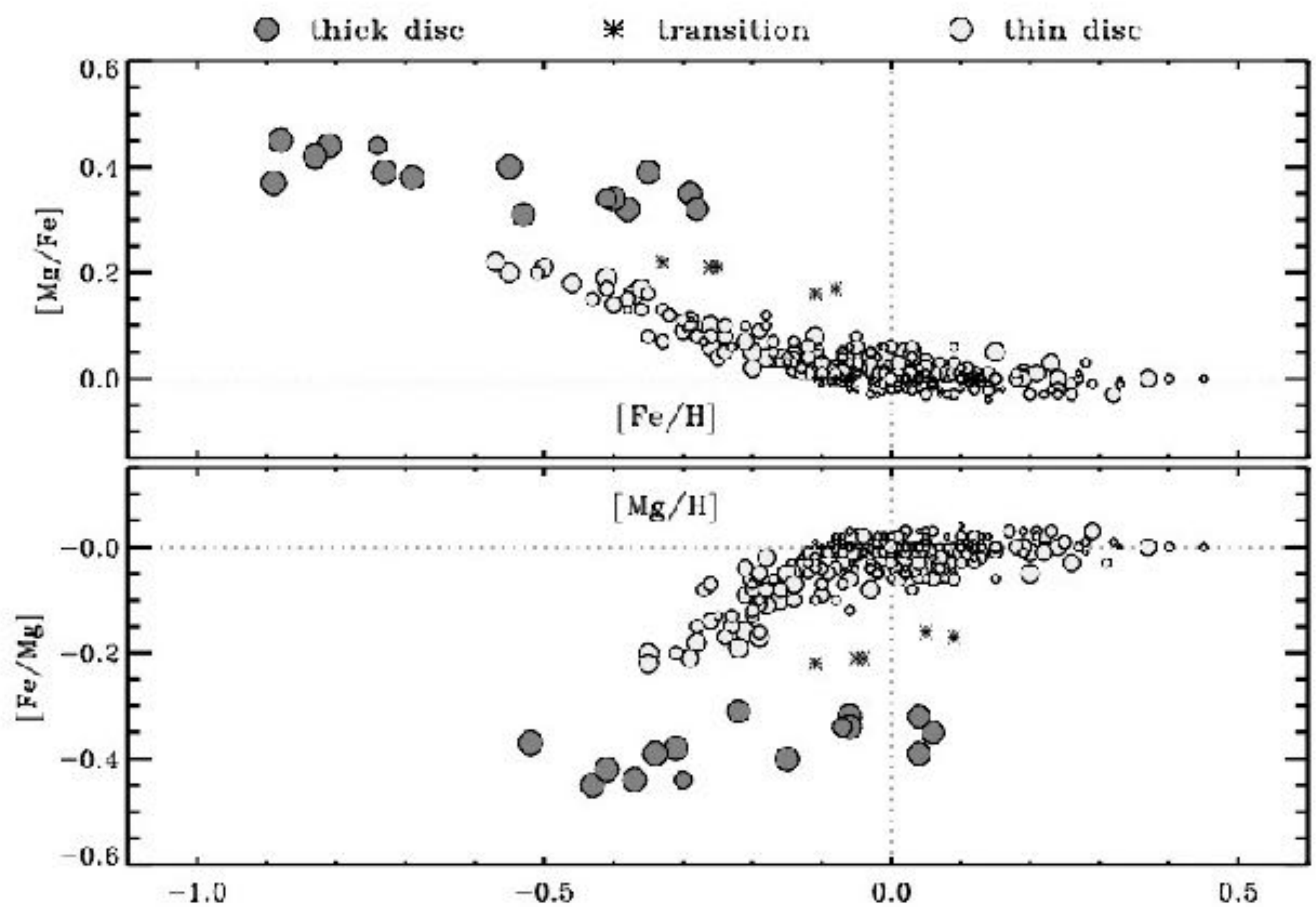
Nearby stars - no selection

- Fuhrmann's study is 85% volume complete for all mid-F type to early K-type stars down to M_V=6, north of dec=-15^o, within a radius d<25pc from the Sun

- Two types of stars:

  1. Old stars with high [Mg/Fe] ratios

  2. Young stars with low [Mg/Fe] ratios



Fuhrmann (1998, 2000, 2004, 2008, 2011)

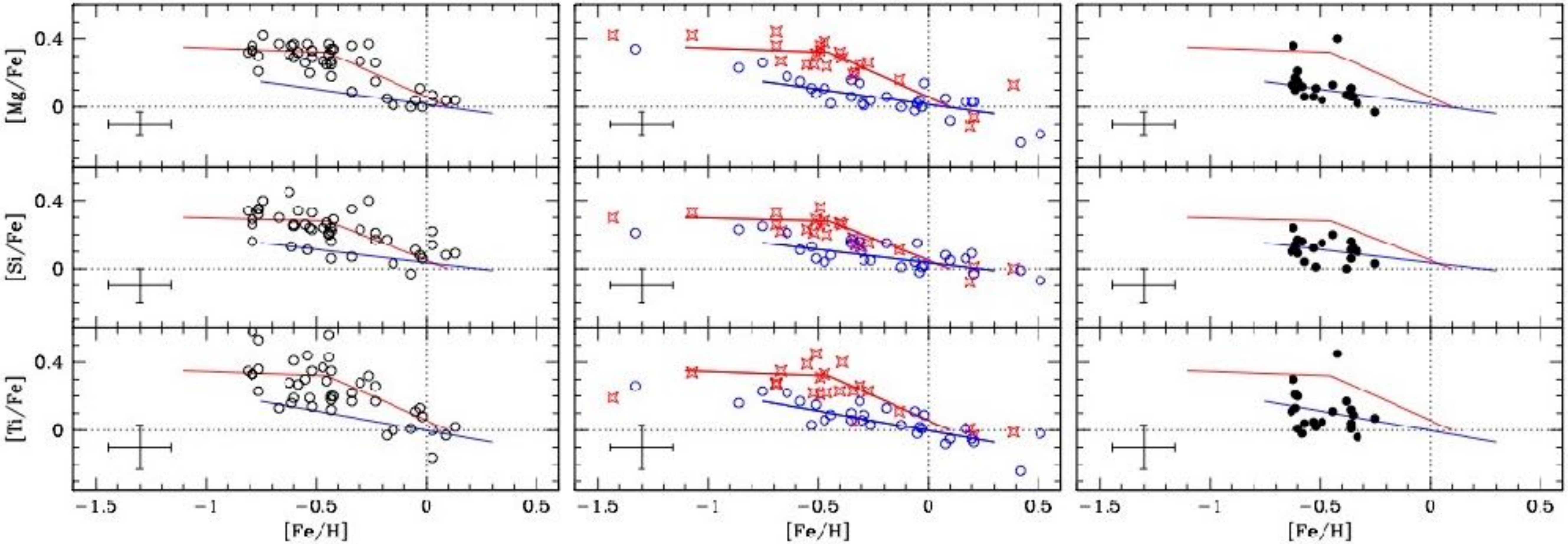
How did they form?

A bit further away

Inner disk
$4 < R_g < 7$ kpc

Solar neighbourhood

Outer disk
$9 < R_g < 13$ kpc



Bensby et al., 2010, A&A, 516, L13

Alves-Brito et al. (2010)

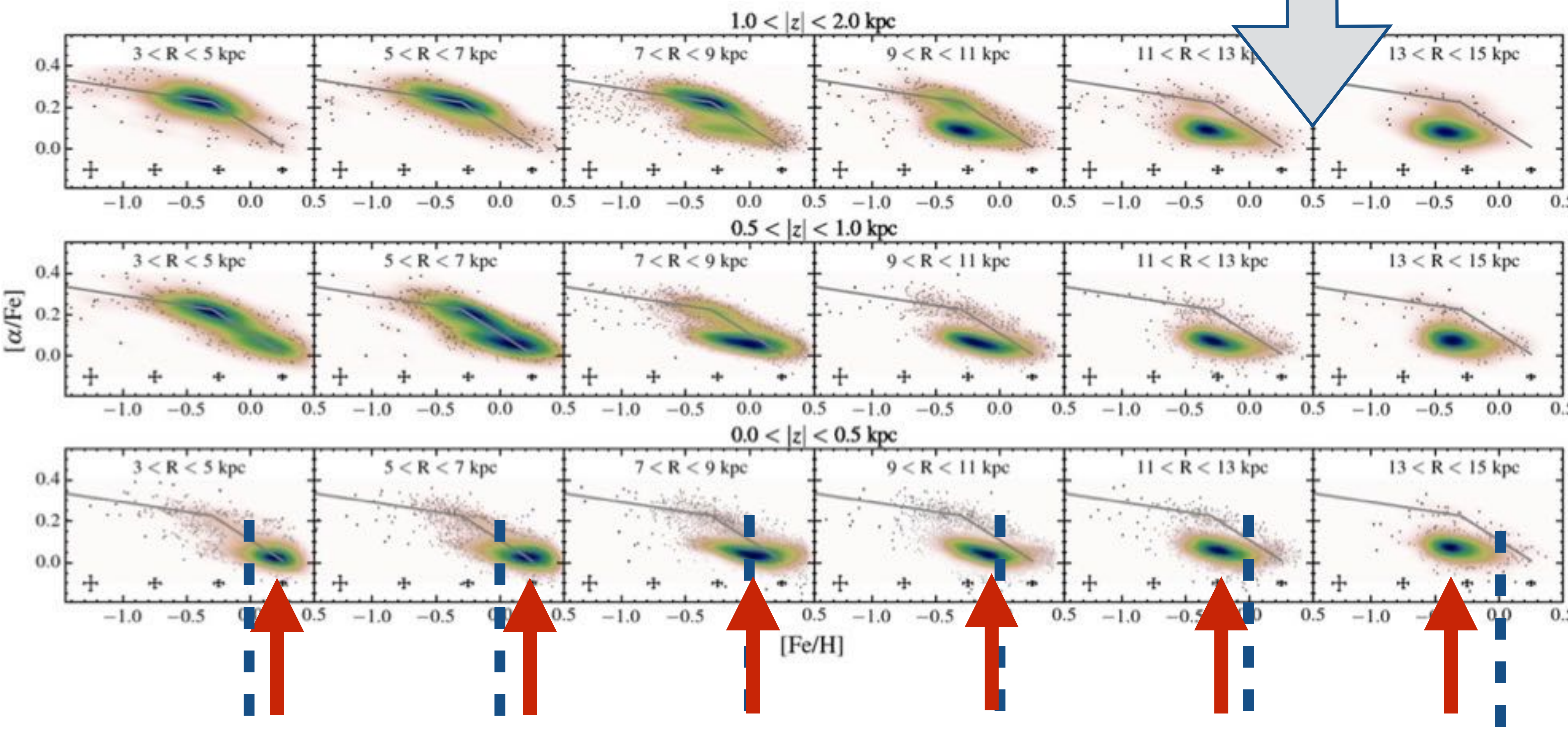
Bensby et al., 2011, ApJ, 735, L46

Short scale-length for the thick disk !

See also, e.g., Cheng et al. (2012), Bovy et al. (2012)

Further away and larger samples - APOGEE

No alpha-enhanced stars!

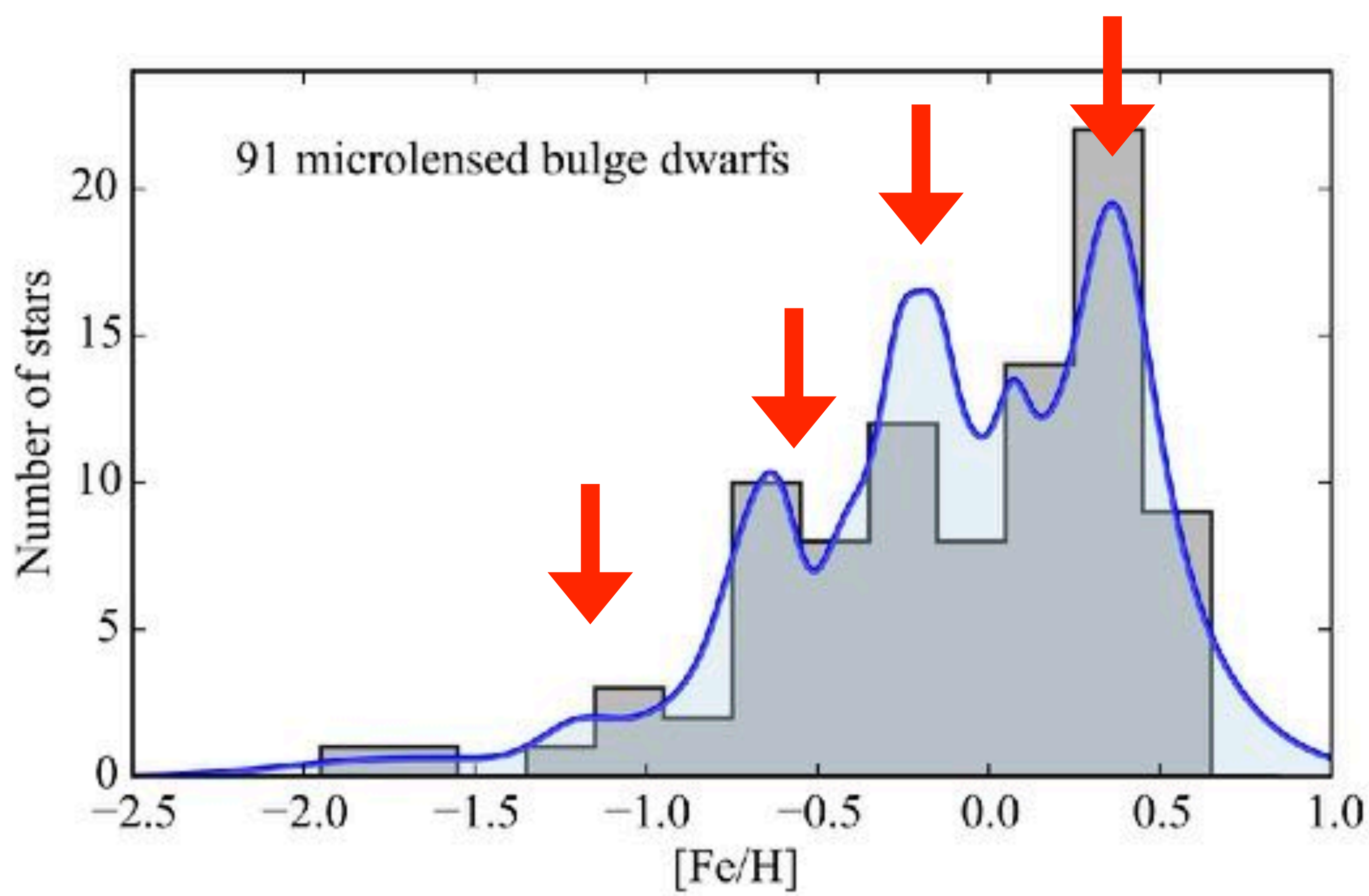


Abundance gradient in the thin disk

- Hayden et al. (2015), based on red giants from APOGEE DR12

The Galactic bulge

Is there *one*, and what about the bar!



- Multiple components
- Lots of young stars (previously the bulge was believed to be all old)

Bensby et al. (2017, A&A)

The outer Galactic disk

A galactic graveyard?

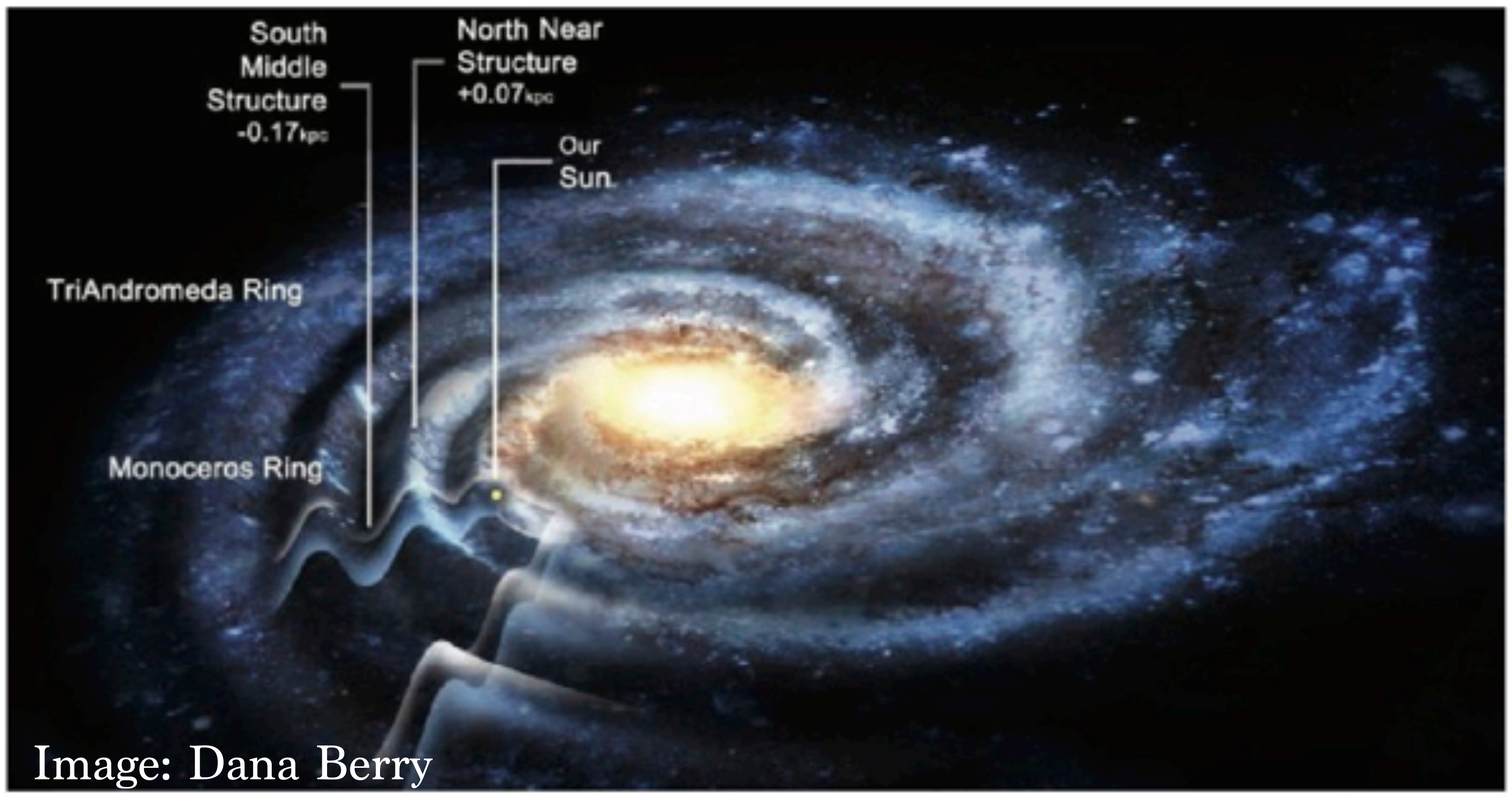


Image: Dana Berry

Ripples from ancient merger events?

Can we identify accreted stars in the disk?

How much of the structure is due to mergers and how much due to internal evolution?

Streams in the Milky Way

Mateu (2023)

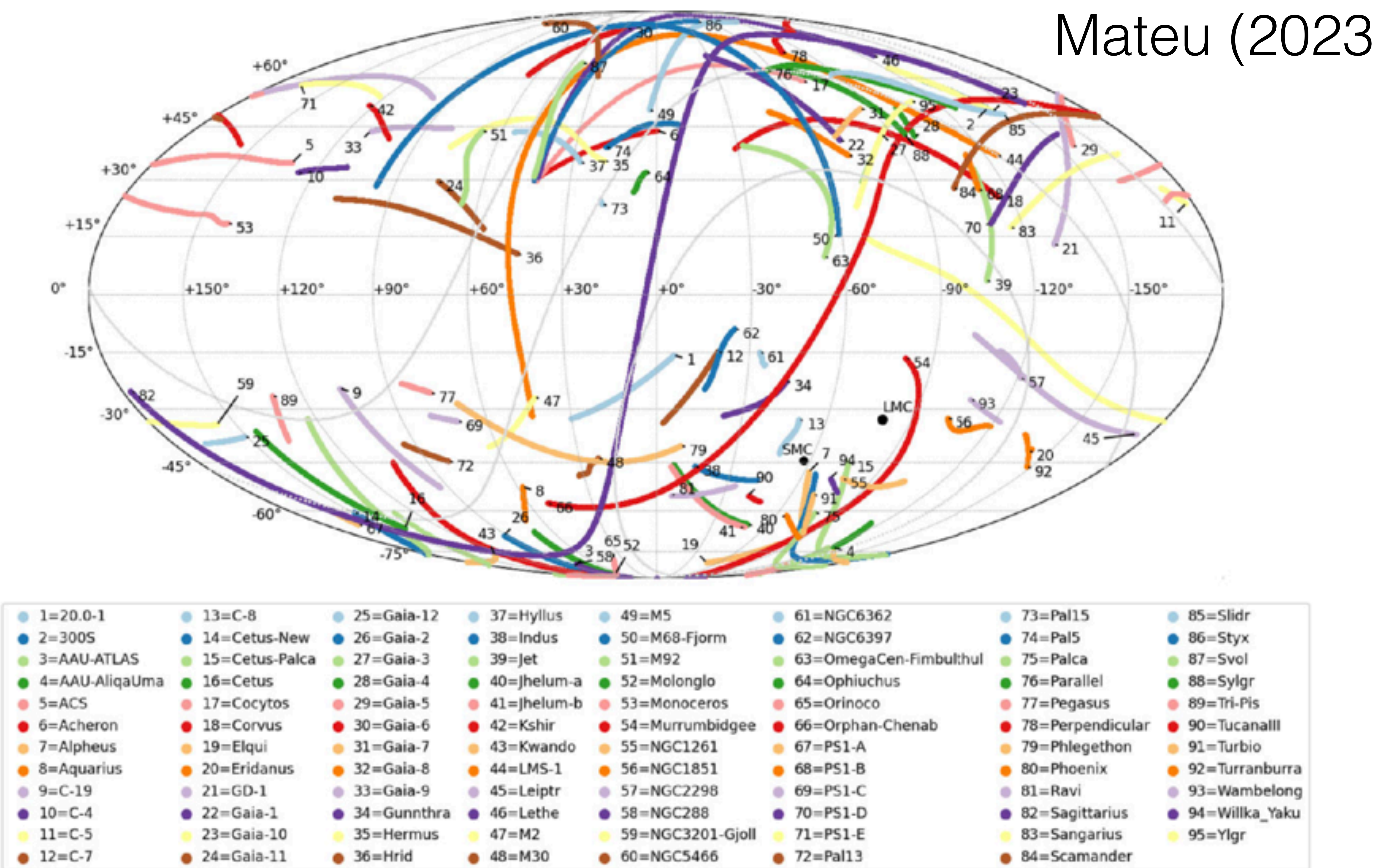
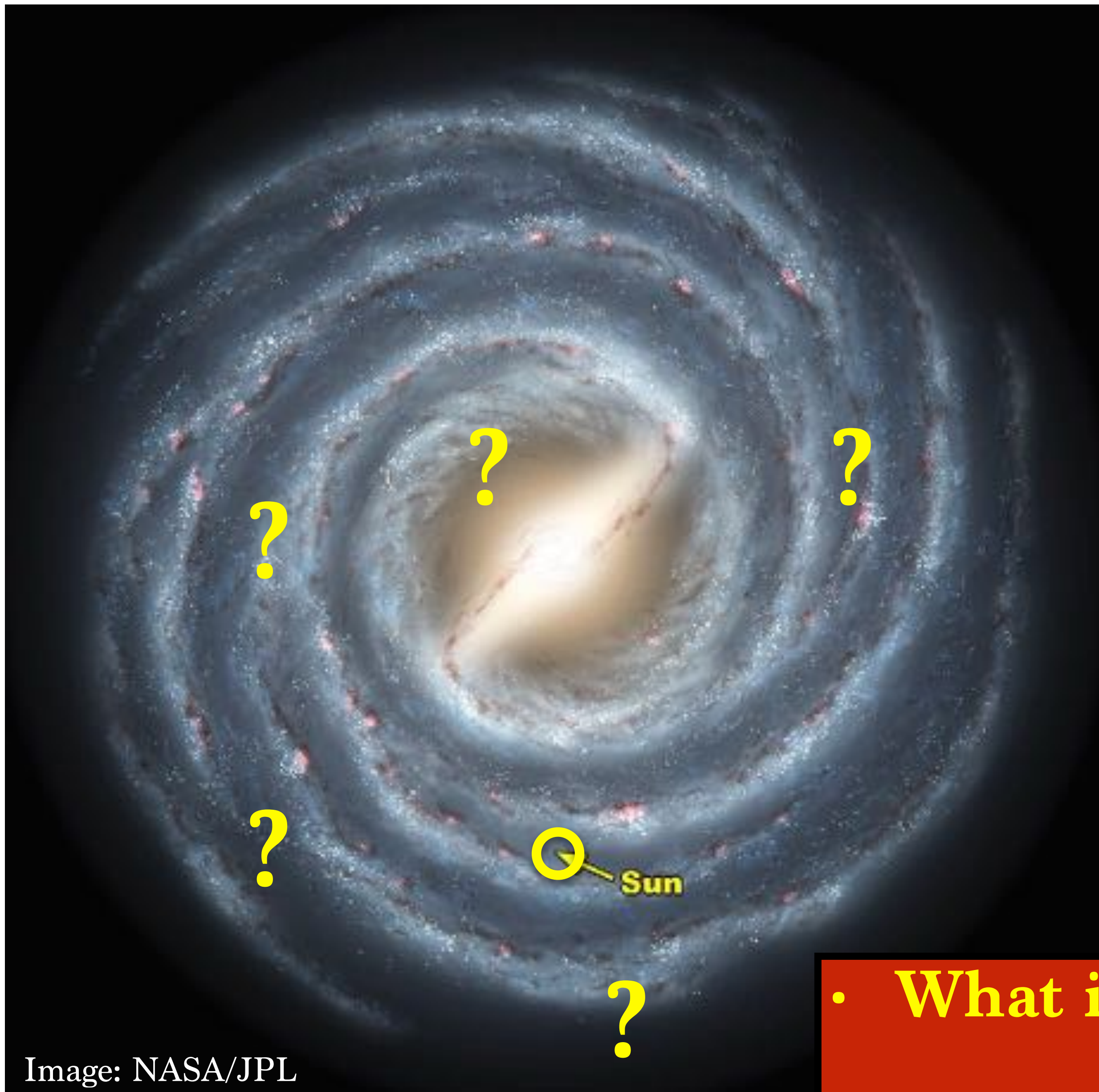


Figure 1. Mollweide projection map in Galactic coordinates of the celestial tracks for the 95 stellar streams implemented in the library. The position of the Large and Small Magellanic Clouds (LMC, SMC) is also shown for reference. The celestial equator and lines of declination +/-30° are shown in gray for reference.

The Milky Way

A benchmark galaxy



- Our home galaxy, one of billions spiral galaxies in the Universe
- The only galaxy where individual stars can be studied in detail
- Most results based on Solar neighbourhood
- Need to map the other regions in detail

- **What is the bulge?**
- **How did the thick disk form?**
- **What is the merger history of the Milky Way?**

Galactic archaeology

using stars to trace the history of our Galaxy

where they are? → positions, distances

how they move? → radial velocities, proper motions

what are they made of? → detailed chemical abundances

+ with stellar models and photometry → ages

Galactic Archaeology

Mapping the Milky Way

Image: Galaxy Puzzle by Lynette Cook

Gaia

Where are the stars?

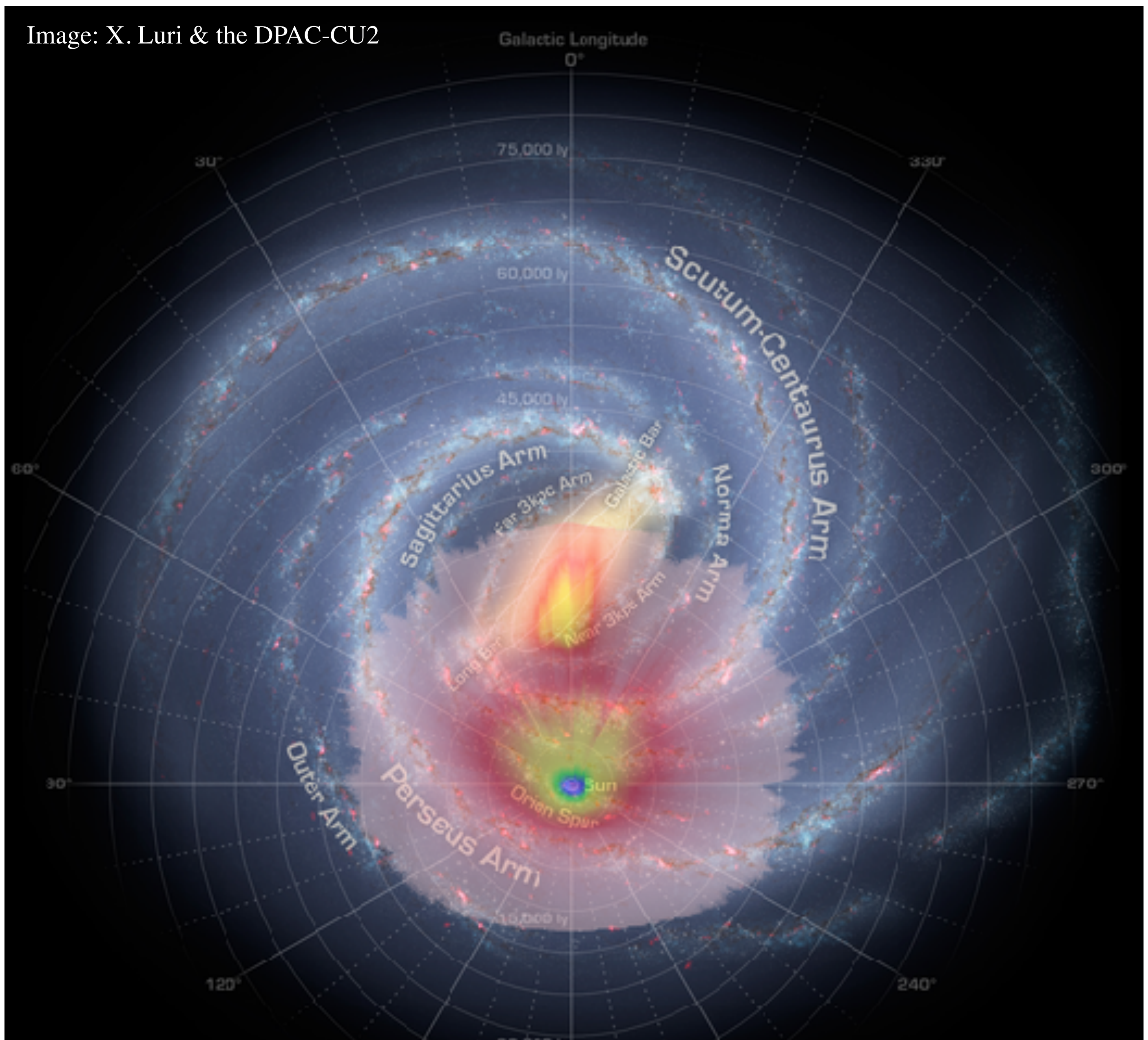


Image: X. Luri & the DPAC-CU2

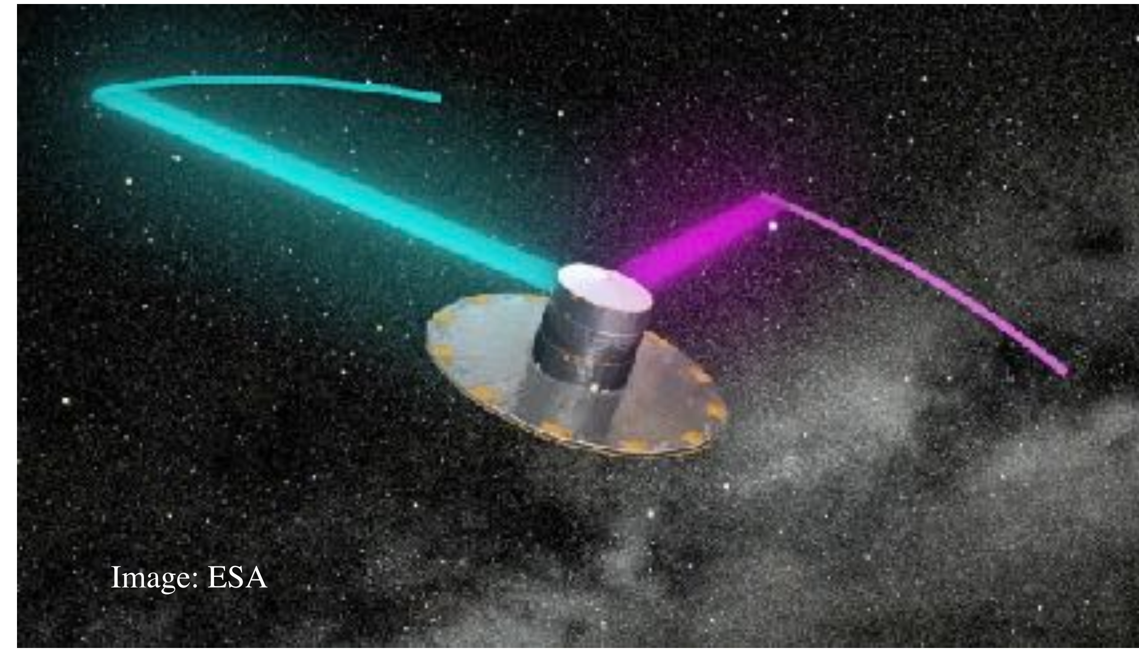


Image: ESA

- Positions
- Distances
- Proper motions
- **1-2 billion stars**

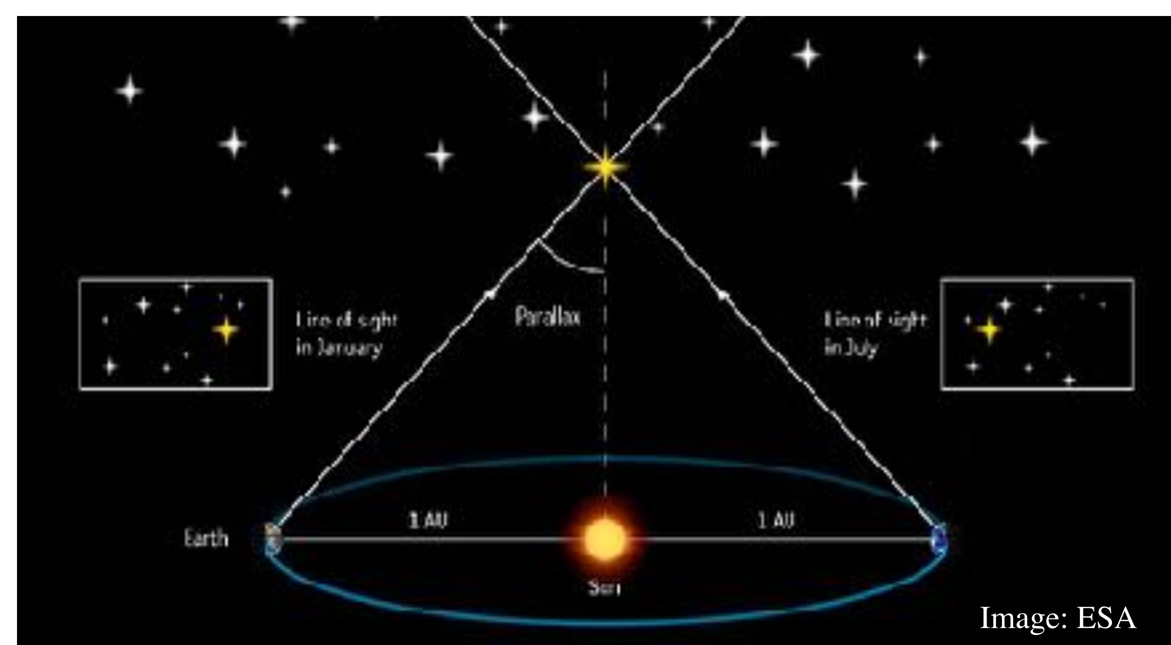
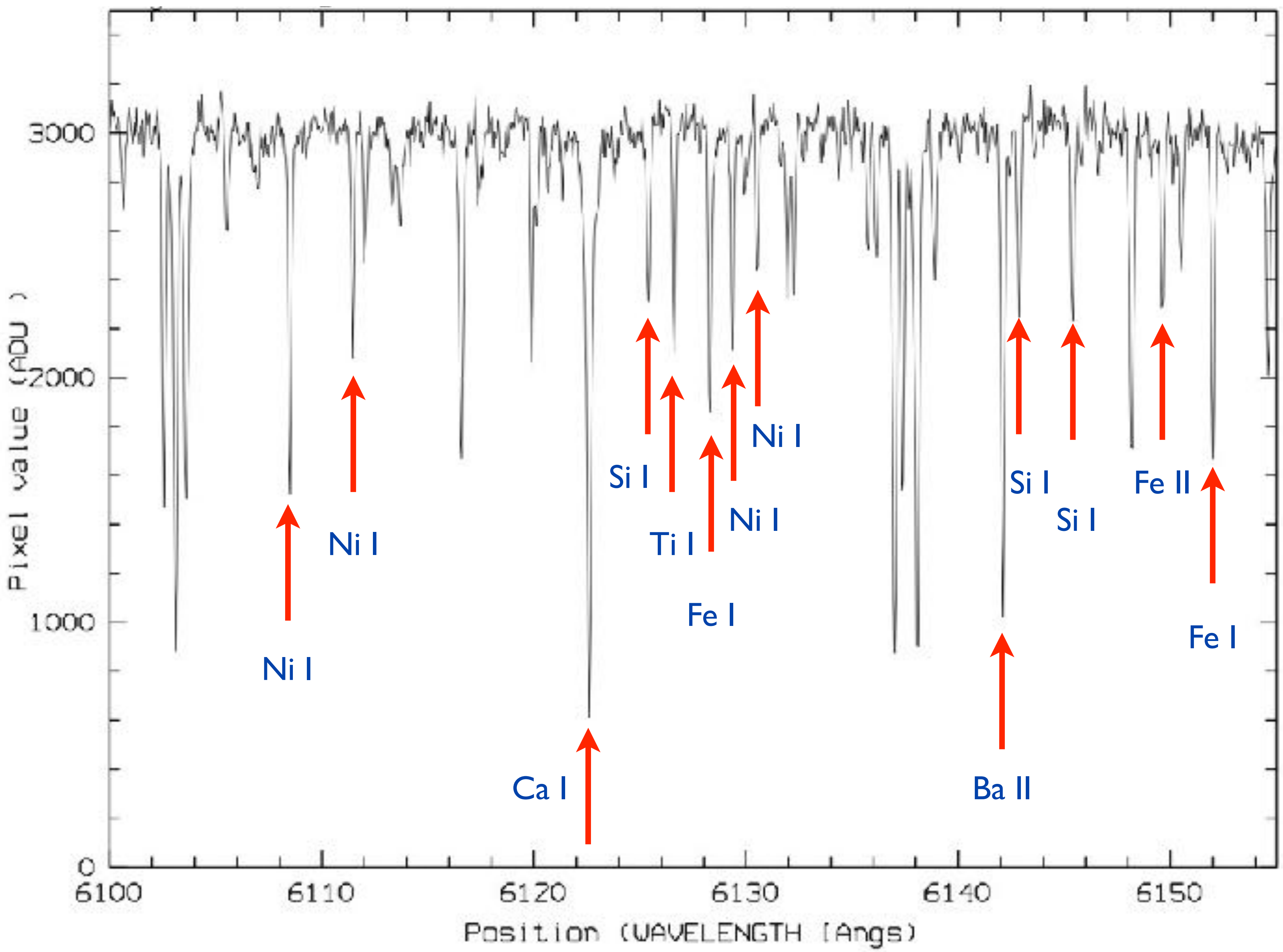


Image: ESA

High-resolution spectroscopy

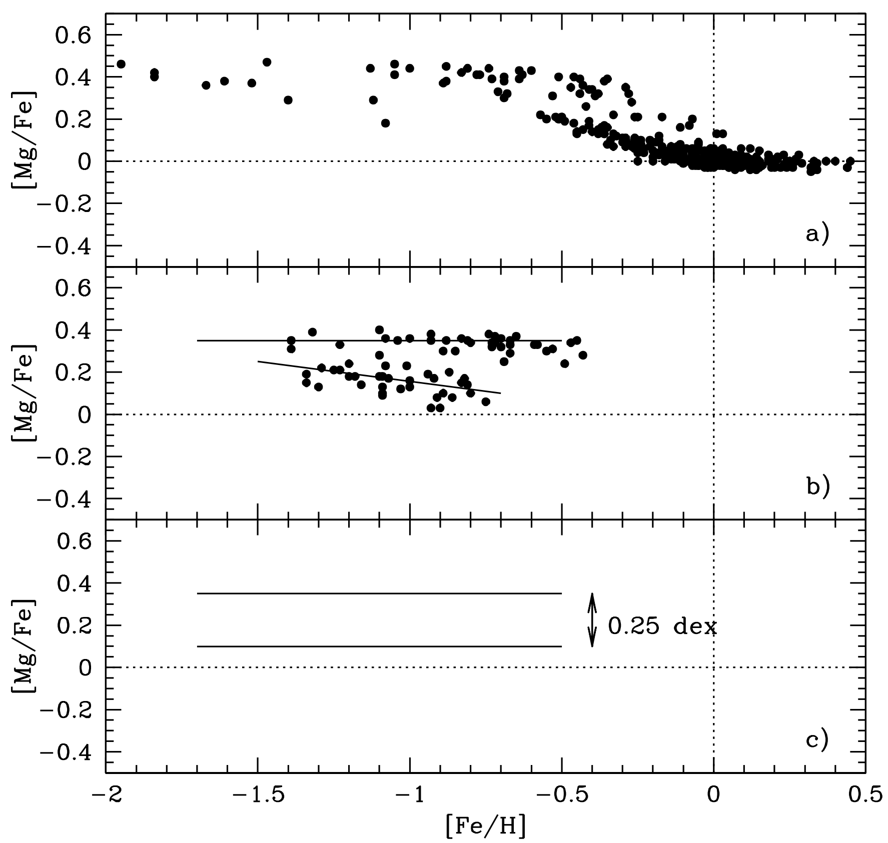
What do the stars consist of?



- Stars are like time capsules
- The atmospheres remain untouched for billions of years
- Traces the chemistry of the gas clouds they were born from

Sample size?

- Better precision will lower the observed dispersion of "structures" and allow us to distinguish them from each other and from the (thin and thick) disk field stars with smaller samples



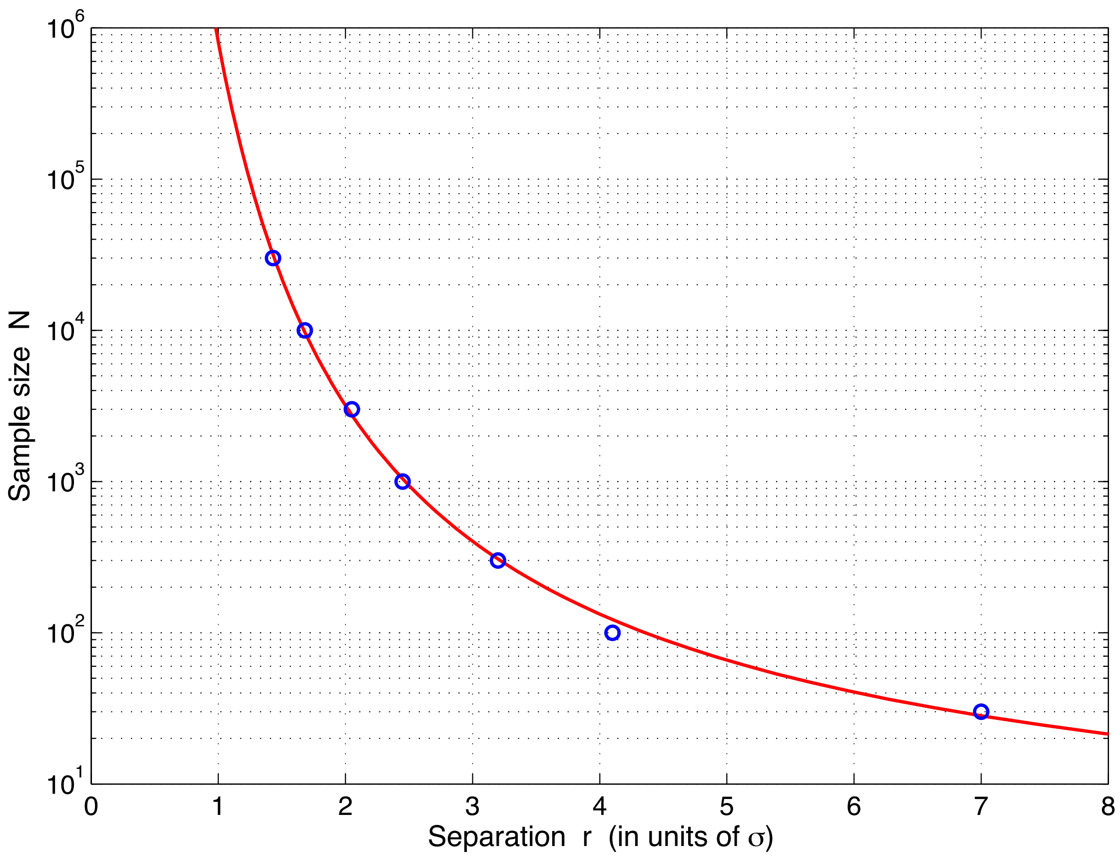
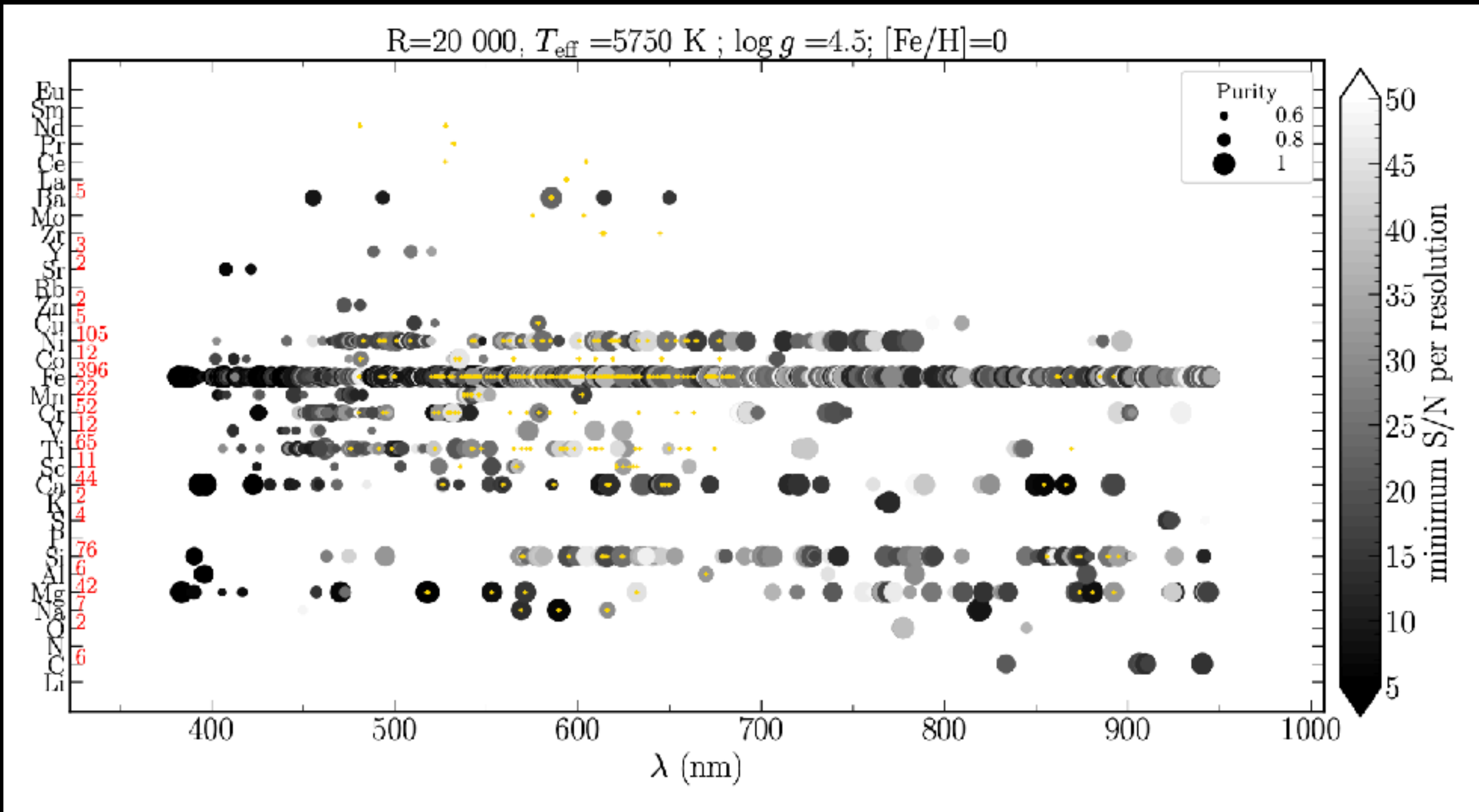


Fig. 4. Minimum sample size needed to distinguish two equal Gaussian populations, as a function of the separation of the population mean in units of the standard deviation of each population. The circles are the results from Monte-Carlo simulations as described in the text, using a K–S type test with significance level $\alpha = 0.01$ and power $1 - \beta = 0.99$. The curve is the fitted function in Eq. (2) or (3).

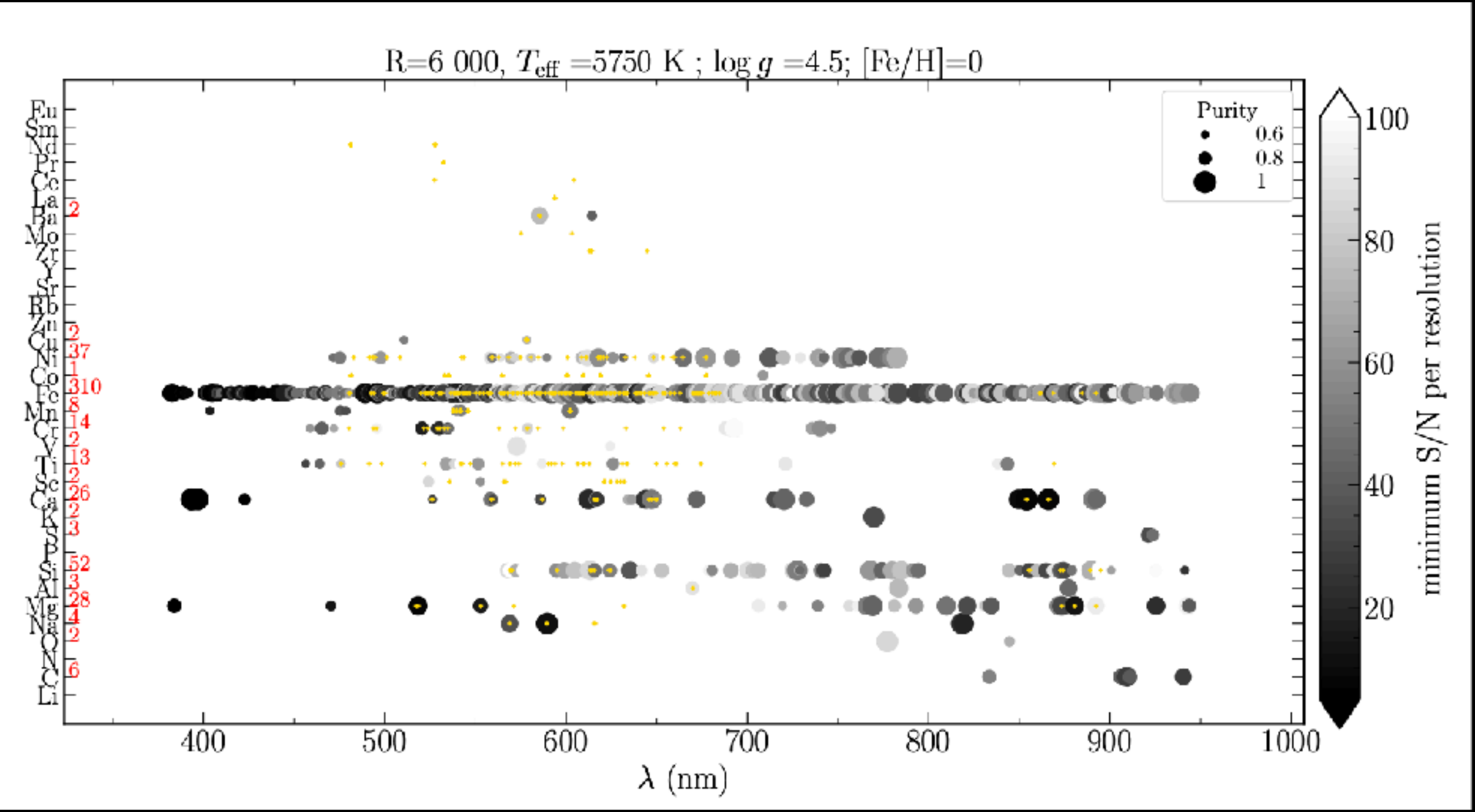
Lindegren & Feltzing (2013)

Resolving power - spectral lines



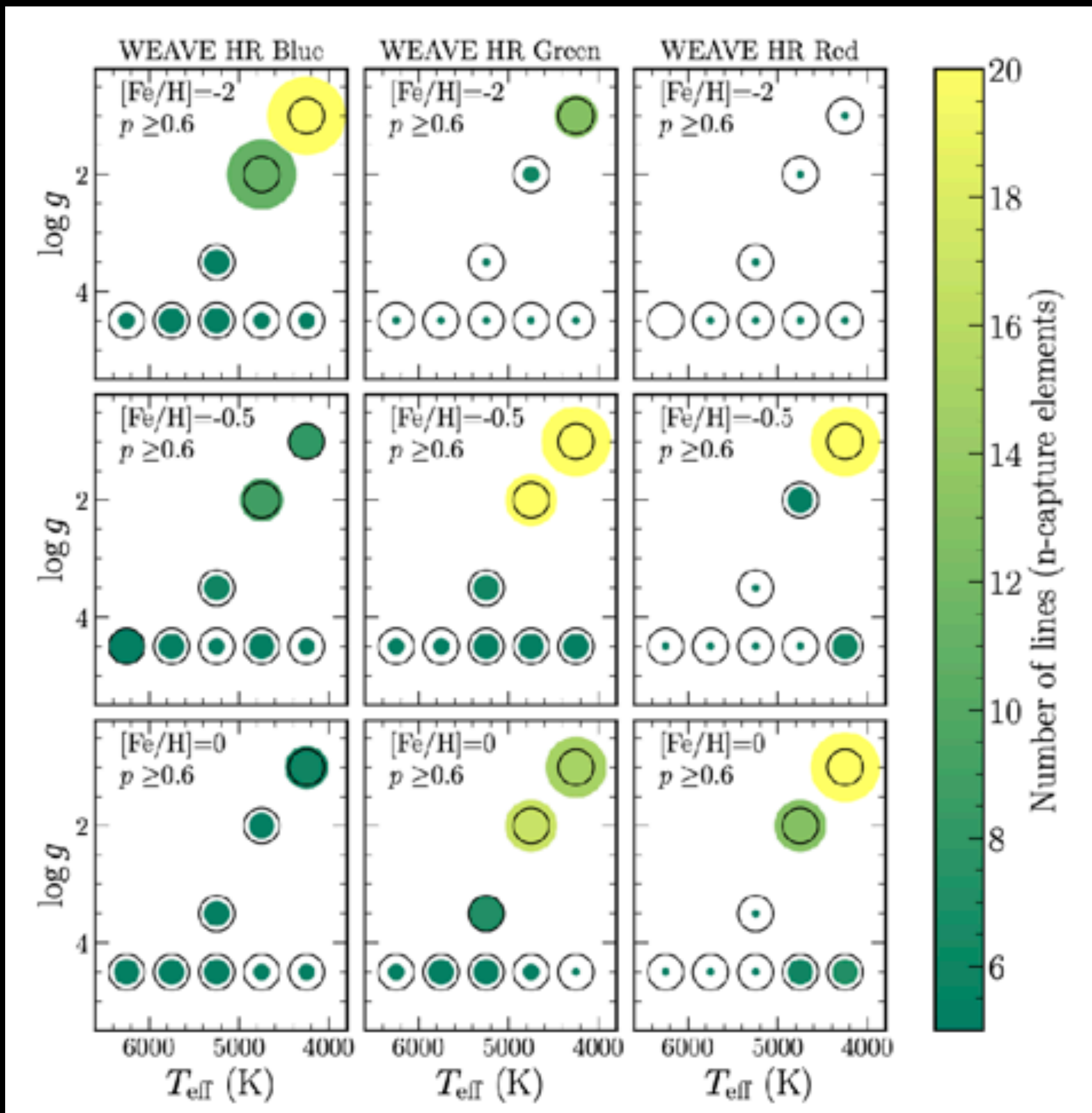
Kordopatis et al. (2023)

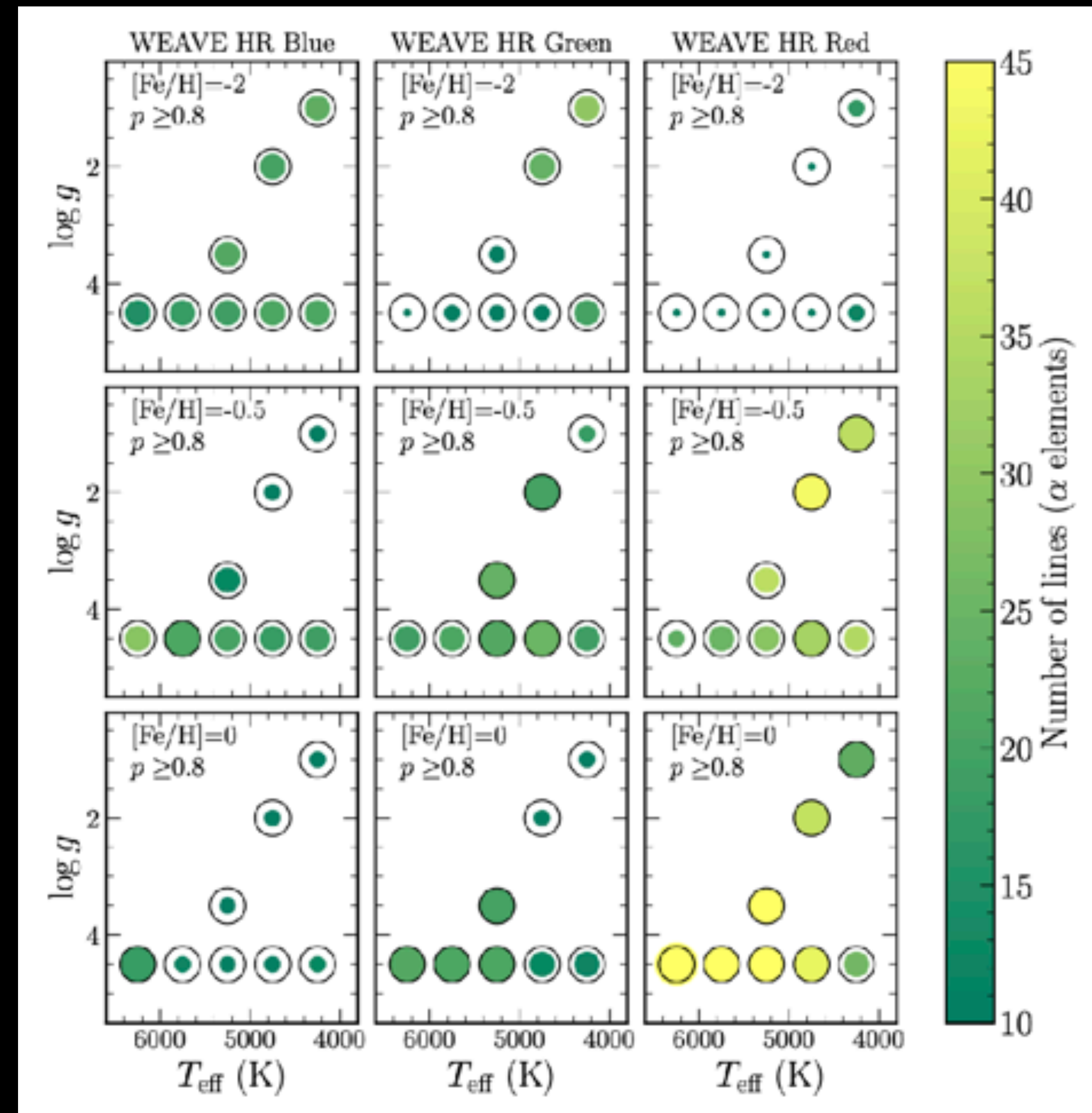
Resolving power - spectral lines



Kordopatis et al. (2023)

Resolving power - spectral lines

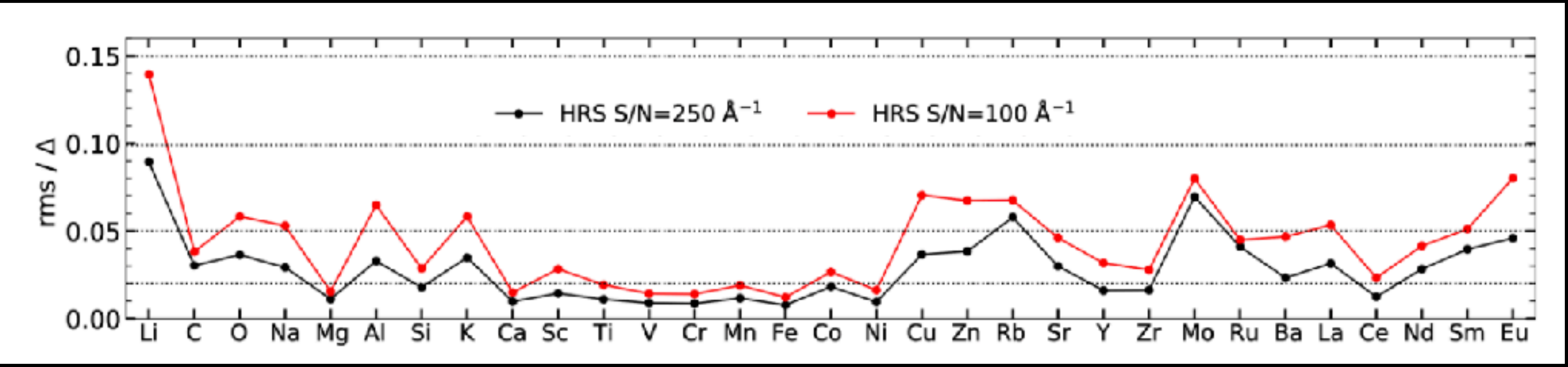




Kordopatis et al. (2023)

4MOST detailed abundances (precision)

Taking advantage of high signal-to-noise (S/N) spectra obtained in three windows: 3926–4355 Å, 5160–5730 Å, and 6100–6790 Å, which allows elements of all main nucleosynthesis channels to be targeted, we will determine abundances of more than 30 elements with a precision better than 0.1 dex



Simulations done with Payne pipeline (see e.g. Kovalev et al., 2019)

4MOST - point source sensitivities

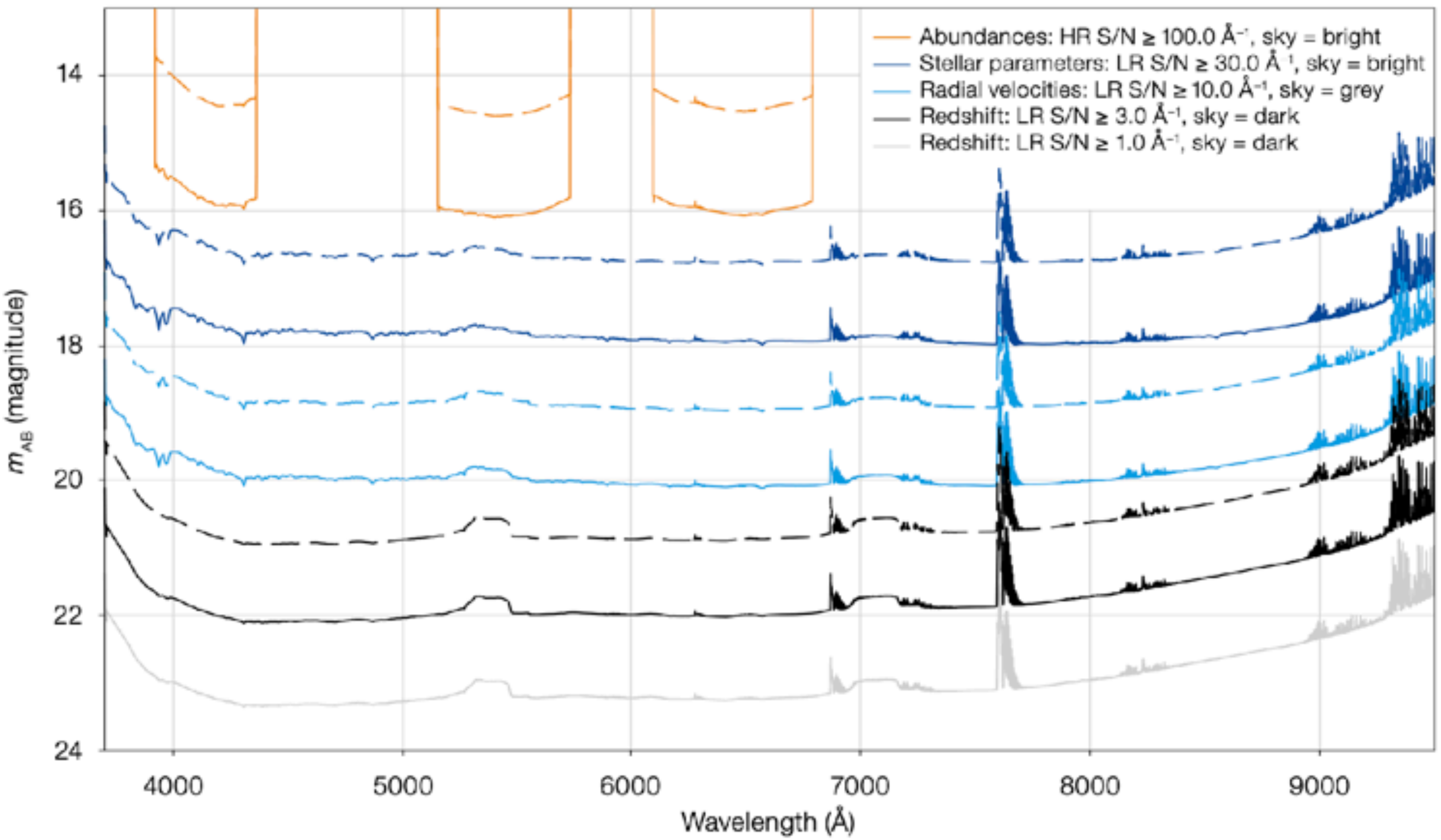


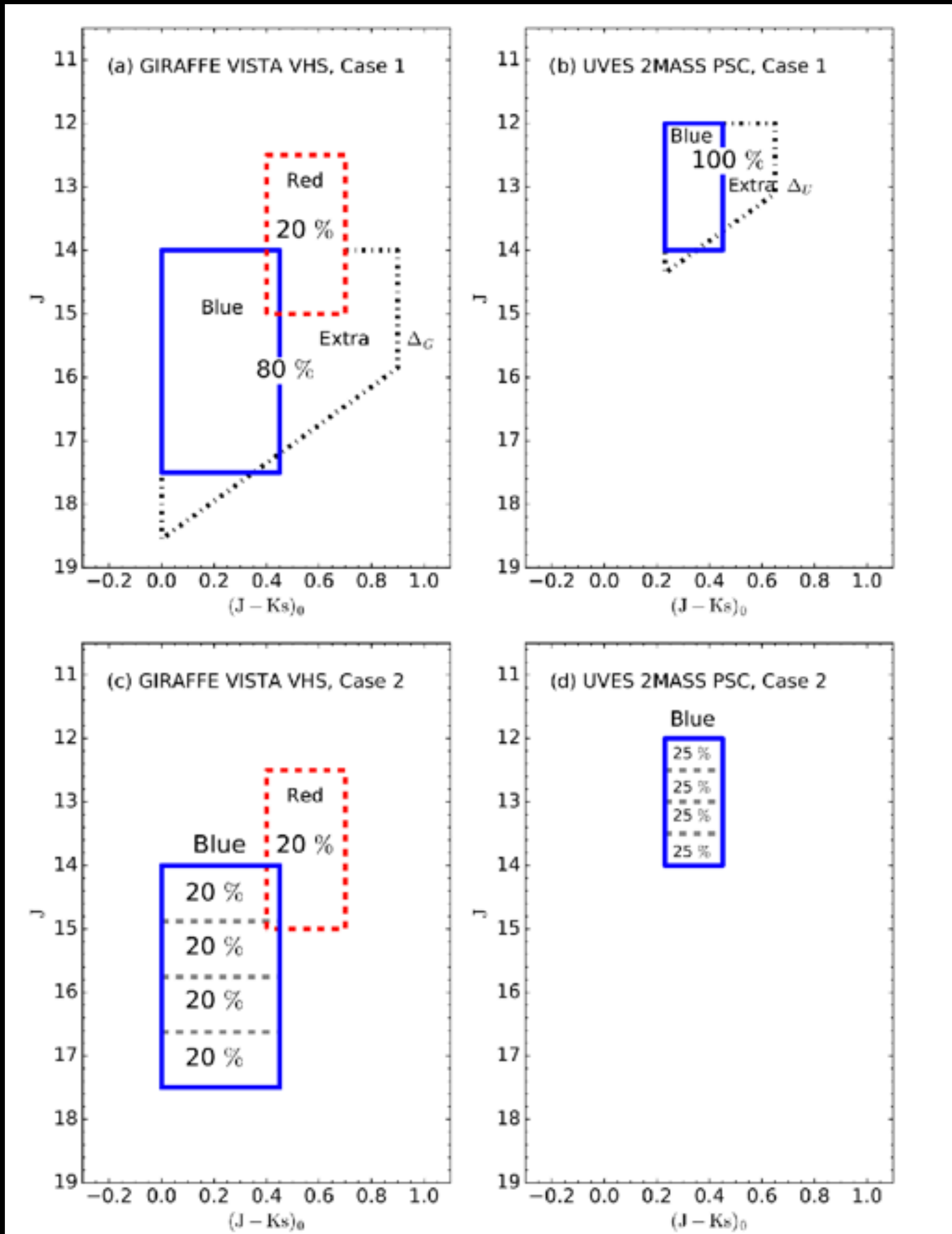
Figure 3. The expected 4MOST point-source sensitivities for the signal-to-noise levels and lunar conditions indicated in the legend. The solid lines are for a total exposure time of 120 minutes, whereas the dashed lines are the limits for 20-minute exposures. The approximate conversion to signal-to-noise per pixel is obtained by dividing the HRS values by 3.3 and the LRS values by 1.7. For clarity, sky emission lines are removed — this mostly affects results redward of 7000 Å. Mean (not median) seeing conditions, airmass values, fibre quality and positioning errors, etc., are used, in order to ensure that this plot is representative for an entire 4MOST survey, not just for the optimal conditions. Typical science cases for obtaining detailed elemental abundances of stars (orange), stellar parameters and some elemental abundances (dark blue), stellar radial velocities (light blue), and galaxy and AGN redshifts (black: 90% complete, grey: 50% complete) are shown.

de Jong (2019)

120 min exposure: solid lines
20 min exposures: dashed lines

SNR values given per Å.
Divide by 3.3 to get to per pixel for HR
Divide by 1.7 to get to per pixel for LR

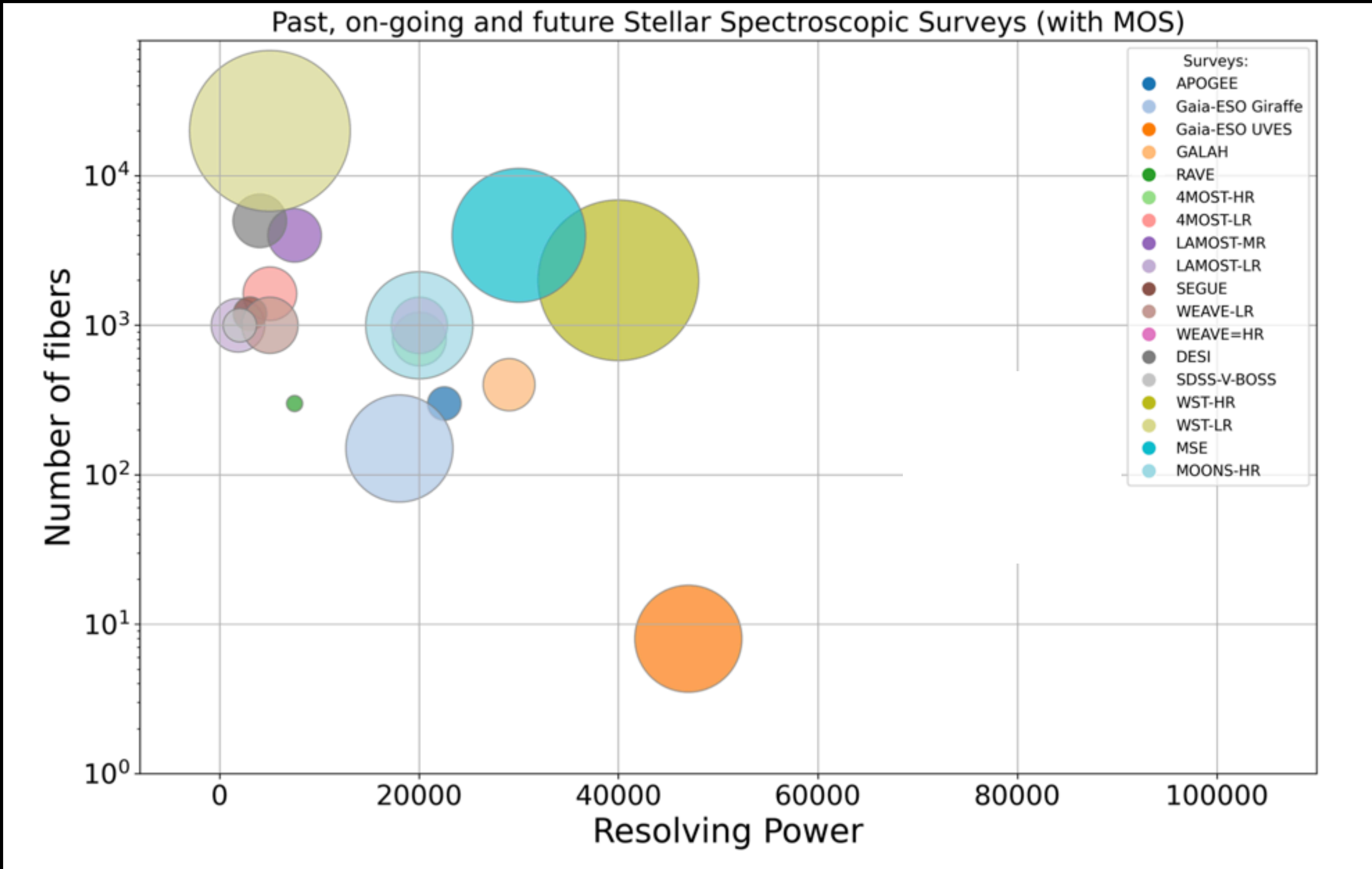
Gaia-ESO selection function



Case 1: when target density is not enough to fill fibres

Case 2: when target density is enough

(Stonkute et al., 2016)



Magrini, Bensby, et al. (2024)

Large Spectroscopic Surveys

Blood samples of millions of stars

VLT

- 130 fibres
- 8-m VLT on Paranal
- 300 nights, 2012-2017
- 100 000 stars

Gilmore et al. (2012, The Messenger, 147, 25)

- 2400 fibres
- 4-m Vista telescope on Paranal
- First light 2025
- 5+5 years
- >10 million stars

de Jong et al. (2019)

Vista

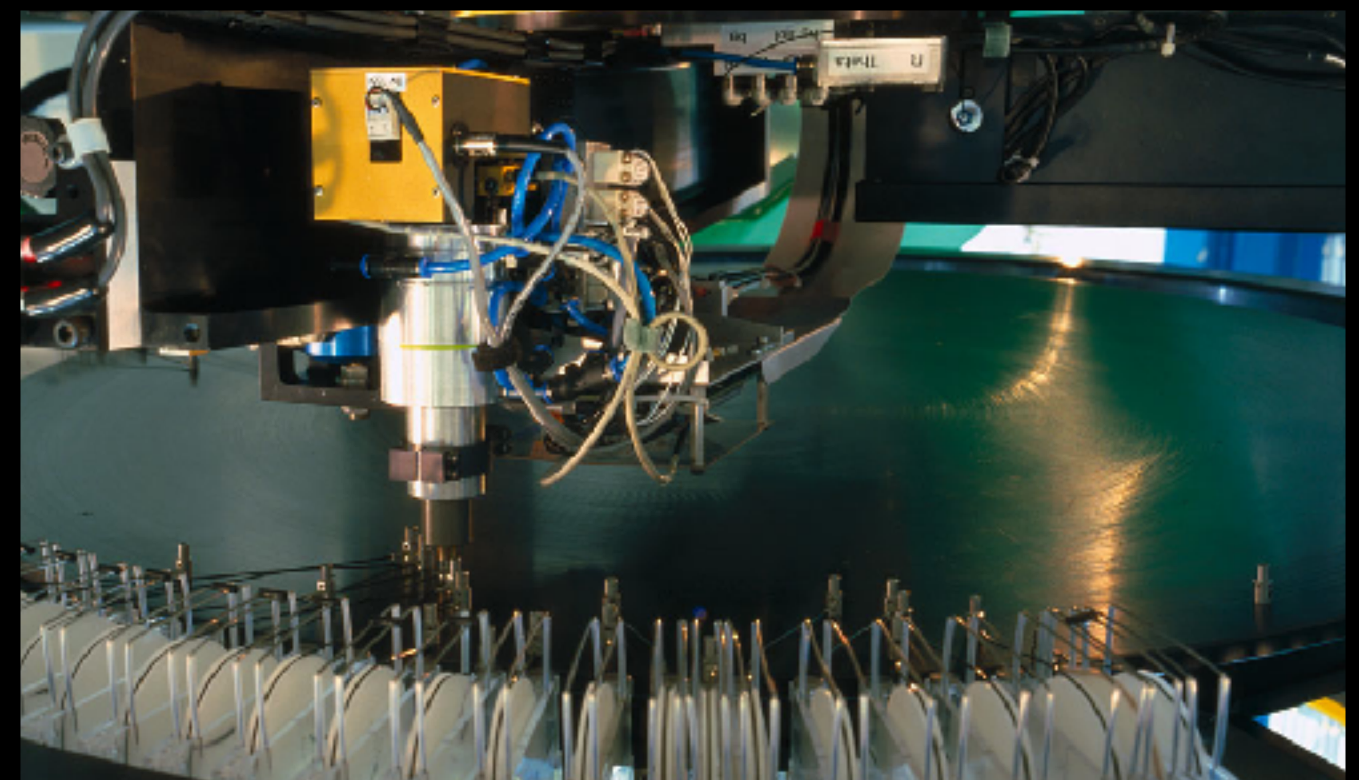
The Gaia-ESO Survey

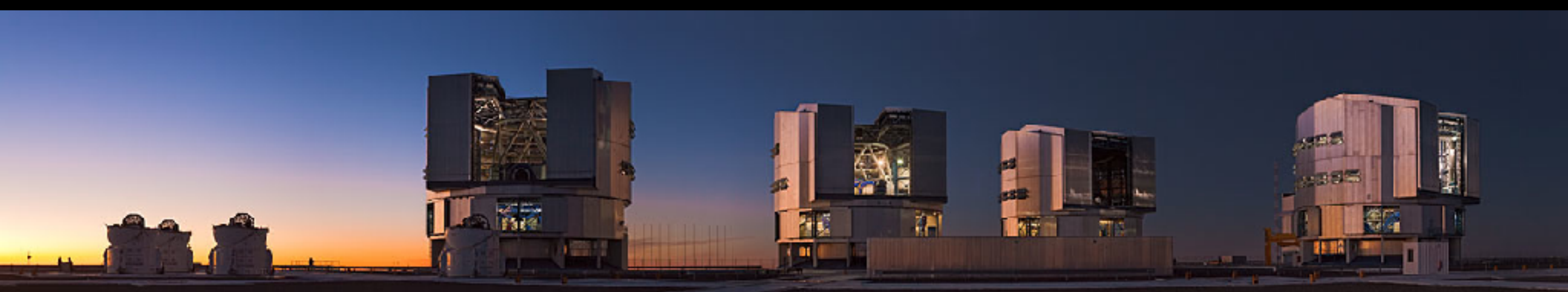
Co-PIs: Gerry Gilmore[1370], Sofia Randich[1335]
CoIs: M. Asplund[1490], J. Binney[1611], P. Bonifacio[1588], J. Drew[1668], S. Feltzing[1473], A. Ferguson[1649], R. Jeffries[1132], G. Micela[1344], I. Negueruela[7609], T. Prusti[1278], H-W. Rix[1489], A. Vallenari[1343], D. Aden[1473], L. Affer[1344], J-M. Alcala[1340], E. Alfaro[1392], C. Allende Prieto[1393], G. Altavilla[7530], J. Alves[1893], T. Antoja[1422], F. Arenou[1588], C. Argiroffi[1881], A. Asensio Ramos[1393], C. Babusiaux[1588], C. Bailer-Jones[1489], L. Balaguer-Nunez[1821], B. Barbuy[1828], G. Barisevicius[1376], D. Barrado y Navascues[1058], C. Battistini[1473], I. Bellas-Velidis[1555], M. Bellazzini[1329], V. Belokurov[1370], T. Bensby[1473], M. Bergemann[1490], G. Bertelli[1343], K. Biazzo[1335], O. Bienayme[1582], J. Bland-Hawthorn[2044], R. Blomme[1650], C. Boeche[2112], S. Bonito[1344], S. Boudreault[1242], J. Bouvier[1449], A. Bragaglia[1337], I. Brandao[1200], A. Brown[1716], J. de Brujine[1278], M. Burleigh[1244], J. Caballero[8545], E. Caffau[2113], F. Calura[1107], R. Capuzzo-Dolcetta[1857], M. Caramazza[1344]. G. Carraro[1261], L. Casagrande[1490], S. Casewell[1244], S. Chapman[1370], C. Chiappini[1135], Y. Chornly[1376], N. Christlieb[1982], M. Cignoni[7530], G. Cocozza[7530], M. Colless[1017], R. Collet[1490], M. Collins[1489], M. Correnti[1329], E. Covino[1340], D. Crnojevic[1649], M. Cropper[1242], M. Cunha[1200], F. Damiani[1344], M. David[1233], A. Delgado[1392], S. Duffau[2112], S. Van Eck [1358], B. Edvardsson[6181], H. Enke[1135], K. Eriksson[2079], N.W. Evans[1370], L. Eyer[1377], B. Famaey[1582], M. Fellhauer[1824], I. Ferreras[1242], F. Figueras[1821], G. Fiorentino[1422], E. Flaccomio[1344], C. Flynn[2044], D. Folho[1200], E. Franciosini[1335], P. Francois[1588], A. Frasca[1341], K. Freeman[1139], Y. Fremat[1650], B. Gaensicke[1241], J. Gameiro[1200], F. Garzon[1393], S. Geier[5677], D. Geisler[1824], B. Gibson[1197], A. Gomboc[1995], A. Gomez[1588], C. Gonzalez-Fernandez[7609], J. Gonzalez Hernandez[1393], E. Grebel[2112], R. Greimel[1423], M. Groenewegen[1650], F. Grundahl[1368], M. Guarcello[1312], B. Gustafsson[2079], P. Hadrava[1116], D. Hadzidimitriou[1559], N. Hambly[1649], P. Hammersley[1258], C. Hansen[2112], M. Haywood[1588], U. Heber[5677], U. Heiter[6181], A. Helmi[1422], G. Hensler[1893], A. Herrero[1393], V. Hill[1591], S. Hodgkin[1370], N. Huelamo[8545], A. Huxor[2112], R. Ibata[1582], M. Irwin[1370], R. Jackson[1132], R. de Jong[1135], P. Jonker[1660], S. Jordan[2112], C. Jordi[1821], A. Jorissen[1358], D. Katz[1588], D. Kawata[1242], S. Keller[1139], N. Kharchenko[1135], R. Klement[1489], A. Klutsch[1803], J. Knude[1966], A. Koch[1244], O. Kochukhov[6181], M. Kontizas[1560], S. Koposov[1370], A. Korn[6181], P. Koubsky[1116], A. Lanzafame[1871], R. Lallement[1588], P. de Laverny[1591], F. van Leeuwen[1370], B. Lemasle[1422], G. Lewis[2044], K. Lind[1490], H.P.E. Lindstrom[1966], J. Lopez santiago[1803], P. Lucas[1668], H. Ludwig[2112], T. Lueftinger[1893], L. Magrini[1335], J. Maiz Apellaniz[1392], J. Maldonado[1803], G. Marconi[1261], G. Matijevic[1995], R. McMahon[1370], S. Messina[1341], M. Meyer[1377], A. Miglio[1359], S. Mikolaitis[1376], I. Minchev[1135], D. Minniti[1801], A. Moitinho[8548], N. Molawi[1583], Y. Momany[1261], L. Monaco[1261], M. Montalto[1200], M.J. Monteiro[1200], R. Monier[5695], D. Montes[1803], A. Mora[1350], E. Moraux[1449], T. Morel[1359], A. Morino[1490], N. Mowlavi[1583], A. Mucciarelli[7530], U. Munari[1343], R. Napiwotzki[1665], N. Nardetto[1824], T. Naylor[1130], G. Nelemans[1638], S. Okamoto[1616], S. Ortolani[6311], G. Pace[1200], F. Palla[1335], J. Palous[1116], E. Pancino[1337], R. Parker[1377], E. Paunzen[1893], J. Penarrubia[1828], I. Pillitteri[1312], G. Piotto[1343], H. Posbic[1588], L. Prisinzano[1344], E. Puzeras[1376], A. Quirrenbach[2112], S. Ragaini[7530], D. Ramano[1337], J. Read[1377], M. Read[1549], A. Recio-Blanco[1591], C. Reyles[1592], N. Robichon[1588], A. Robin[1592], S. Roeser[2112], F. Royer[1588], G. Ruchti[1490], A. Ruzicka[1116], S. Ryan[1668], N. Ryde[1473], G. Sacco[1645], N. Santos[1200], J. Sanz Forcada[1456], L.M. Sarro Baro[5688], L. Sbordone[1139], E. Schilbach[2112], S. Schmeja[2112], O. Schnurr[1135], R. Schoenrich[1490], R-D. Scholz[1135], G. Seabroke[1242], S. Sharma[2044], G. De Silva[1017], R. Smiljanic[1258], M. Smith[1616], E. Solano[8545], C. Soubiran[1592], S. Sousa[1200], A. Spagna[1346], M. Steffen[1135], M. Steinmetz[1135], B. Stelzer[1344], E. Stempels[6181], H. Tabernero[1803], G. Tautvaisiene[1376], F. Thevenin[1591], J. Torra[1821], M. Tosi[1337], E. Tolstoy[1422], C. Turon[1588], M. Walker[1312], N. Walton[1370], J. Wambsganss[2112], C. Worley[1591], K. Venn[2061], J. Vink[1111], R. Wyse[1419], S. Zaggia[1343], W. Zeilinger[1893], M. Zoccali[1801], J. Zorec[1361], D. Zucker[1477], T. Zwitter[1995]

The *Gaia*-ESO Survey

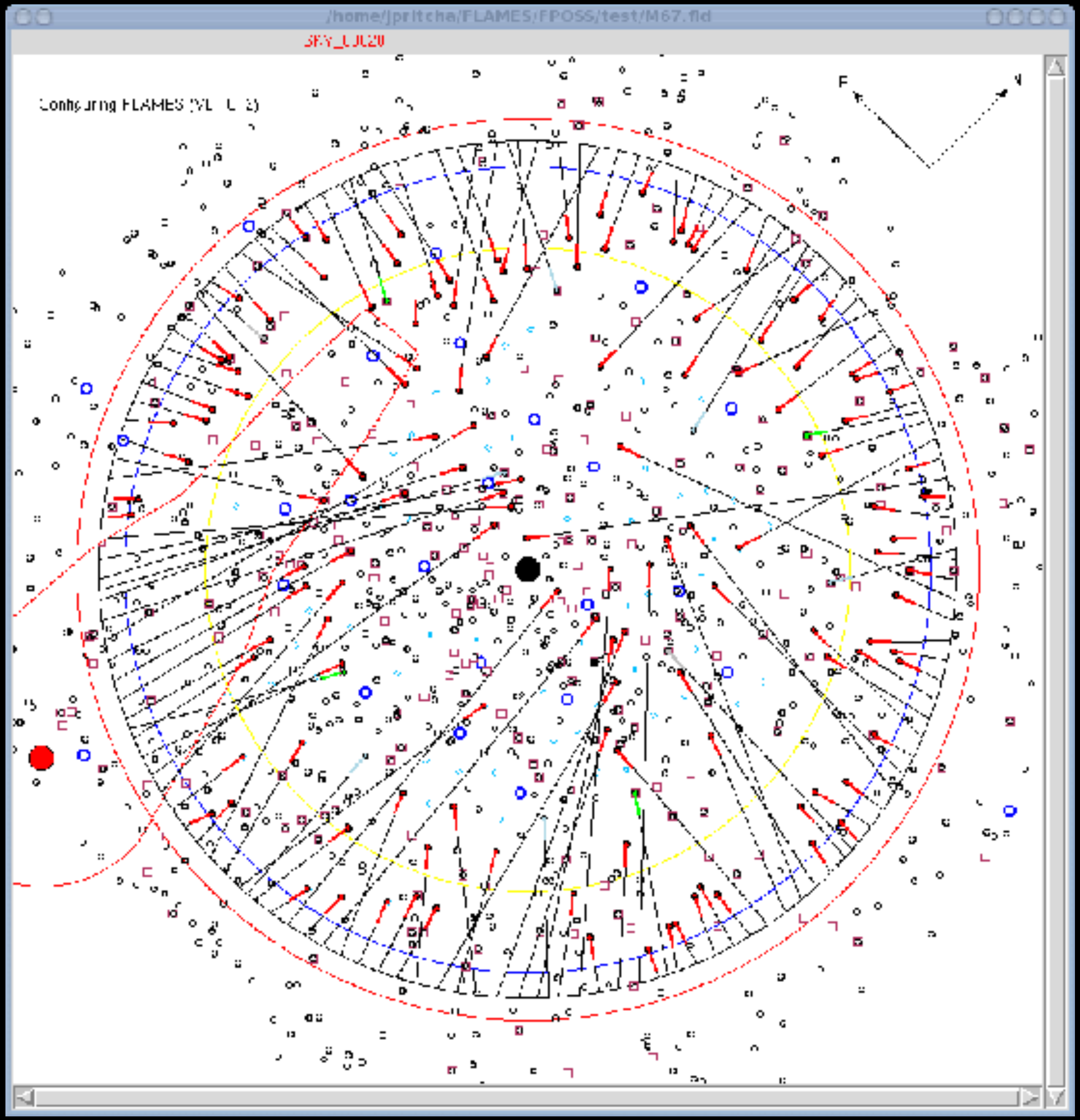
Gilmore et al. (2012, The Messenger, 147, 25)
Randich et al. (2013, The Messenger, 154, 47)

- >400 collaborators
- 300 nights over 5 years with FLAMES on VLT
- 100 000 stars, thin/thick disk, halo, bulge, open clusters, globular clusters, and more….
- Largest spectroscopic survey on an 8-m class telescope



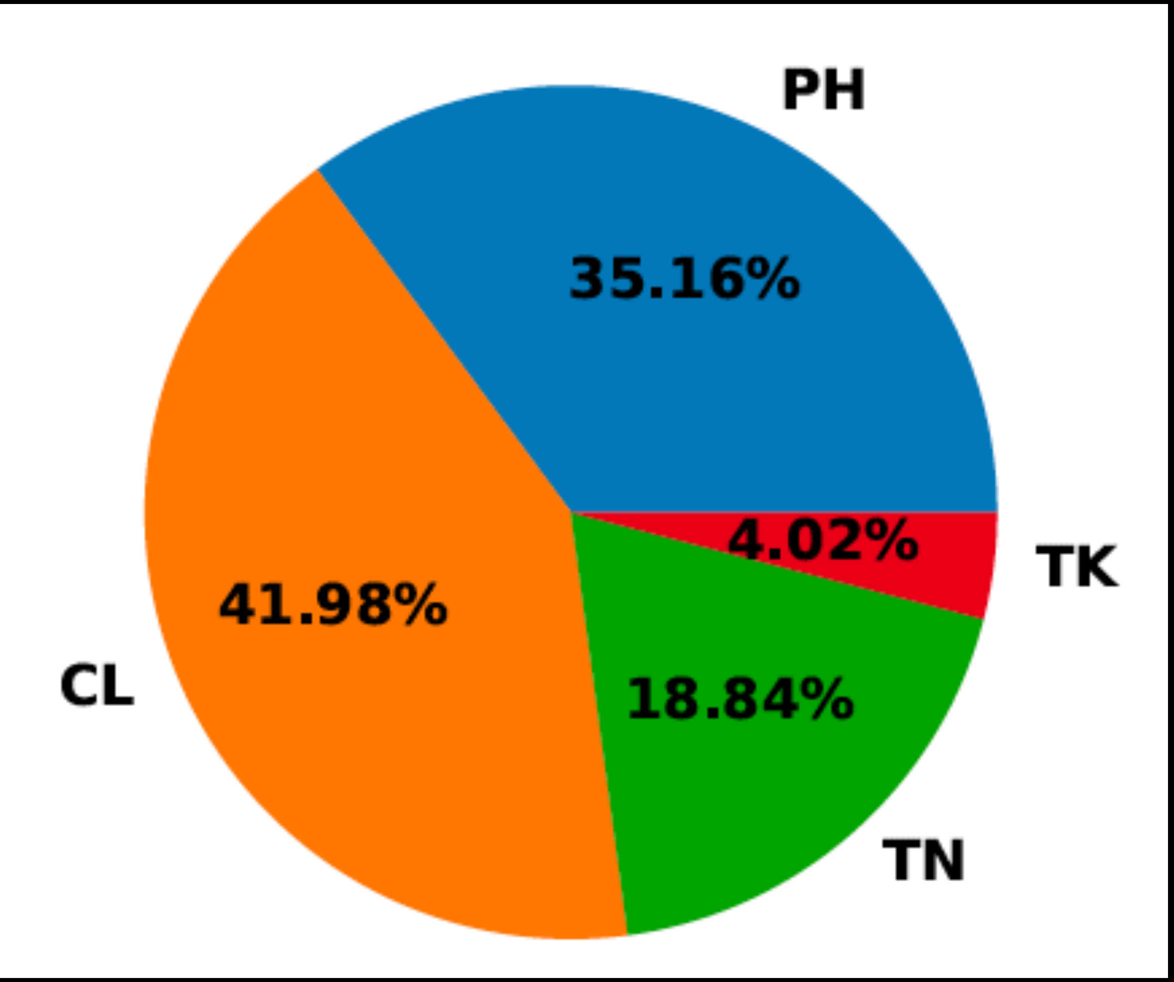


FPOSS

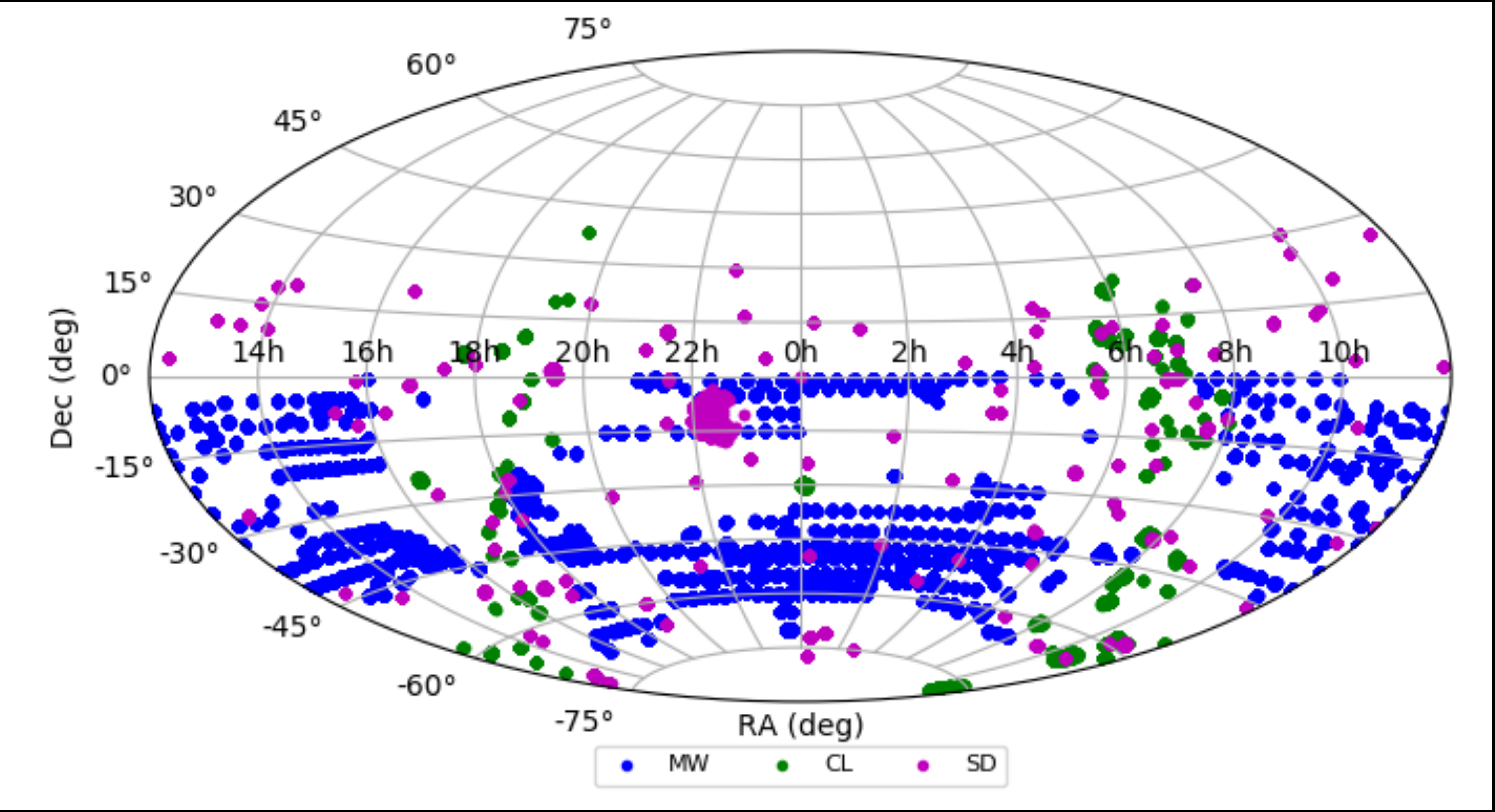


Observations

- 340 nights from Dec 31, 2011 (P88) - Jan 2018 (P100)
- 19% completely lost due to bad weather



Observed fields



Number of spectra

Set-up	# Spectra MW	# Spectra CL	# Spectra SD	Approx. # spectra total
HR10	53912	492	6175	60579
HR21	59381	491	7647	67519
HR03	0	2266	233	2499
HR04	0	1294	0	1294
HR05A	0	2055	218	2273
HR06	0	2160	214	2374
HR14A	0	2036	431	2467
HR09B	0	3627	934	4561
HR15N	0	36524	5235	41759
U520	0	668	1200	1868
U580	7300	3724	3546	14570
All				201763

Abundance analysis

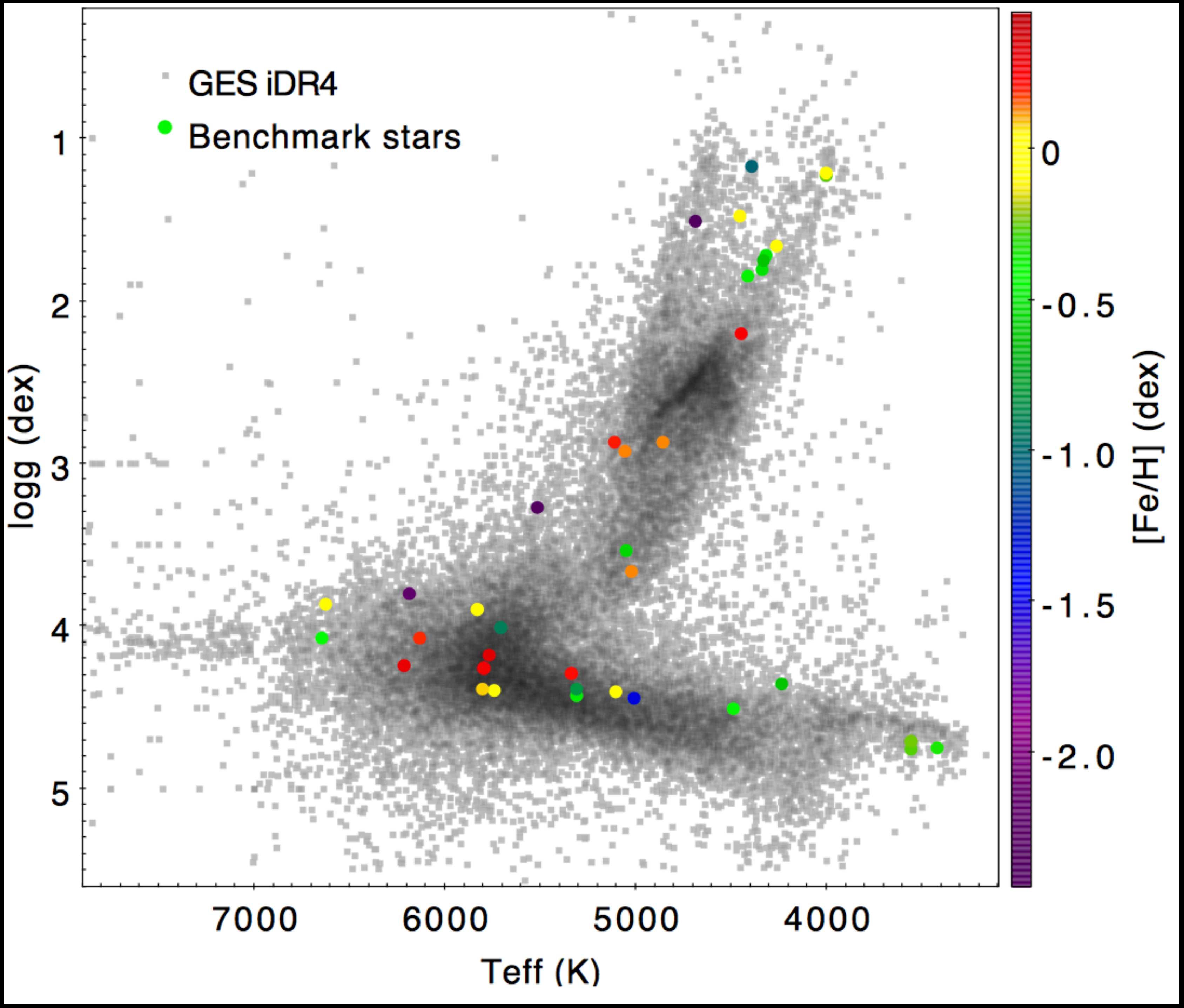
- GIRAFFE data reduced at CASU with the pipeline developed by Jim Lewis

- UVES data reduced in Arcetri with an improved version of the ESO pipeline

- The abundance analysis is done by many nodes, using different methods. Homogenisation is done and weighted based on how well the nodes perform on the Gaia Benchmark stars

- Realised the importance of using common line list, common model atmospheres, common grid of synthetic spectra.

Parameter space

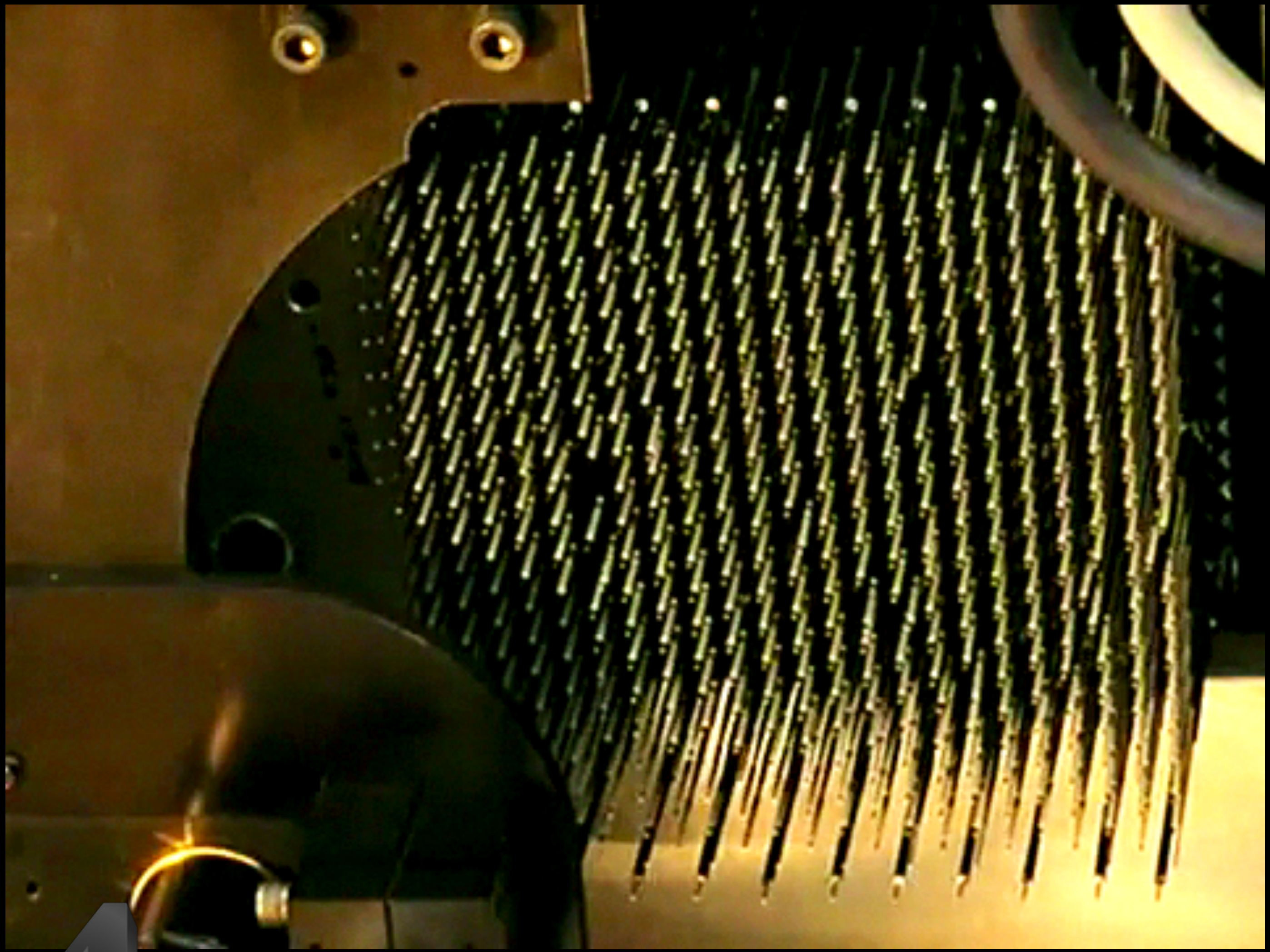


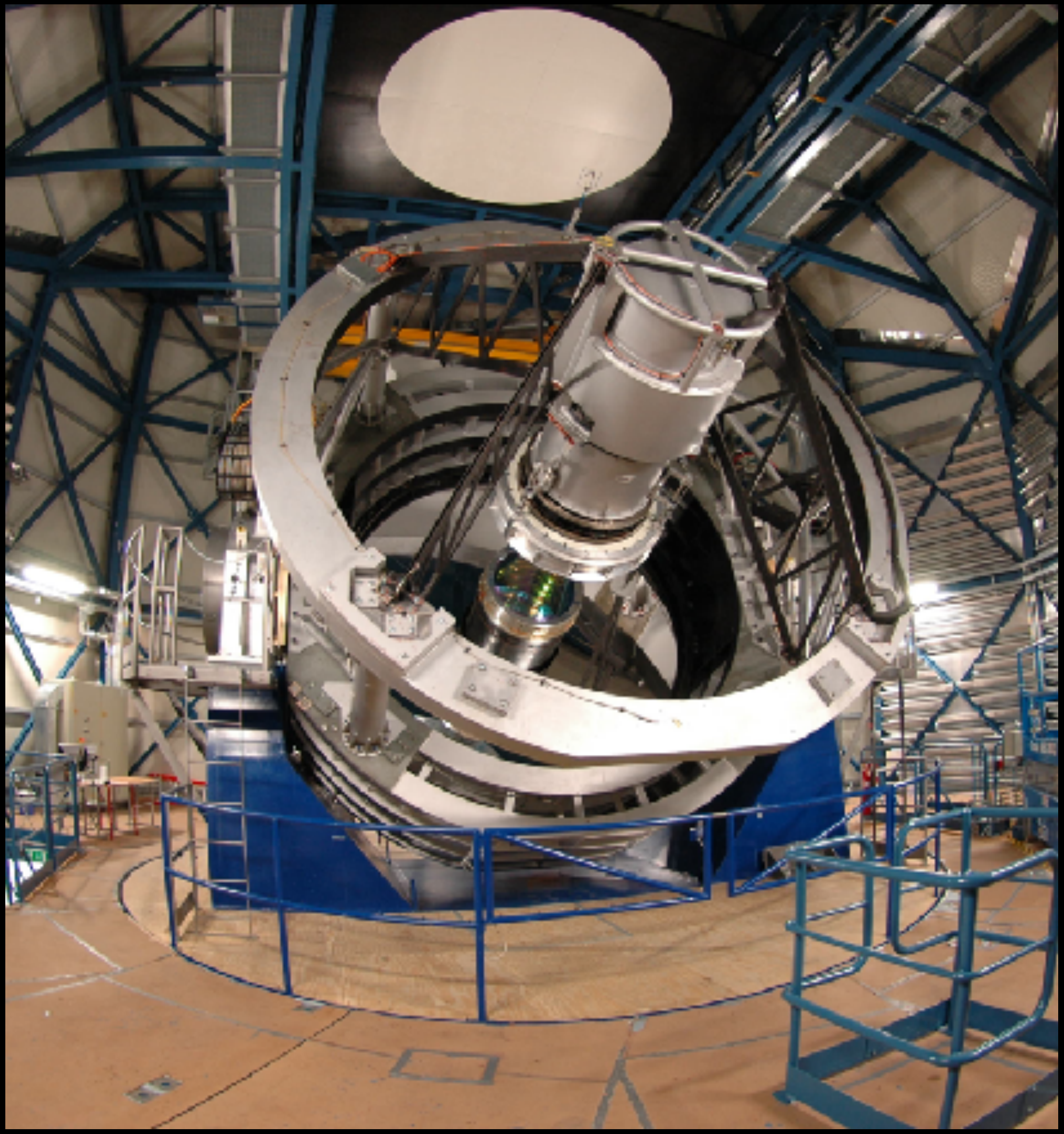
Benchmark stars from Heiter et al (2015), figure from Pancino et al. (2017)

4MOST

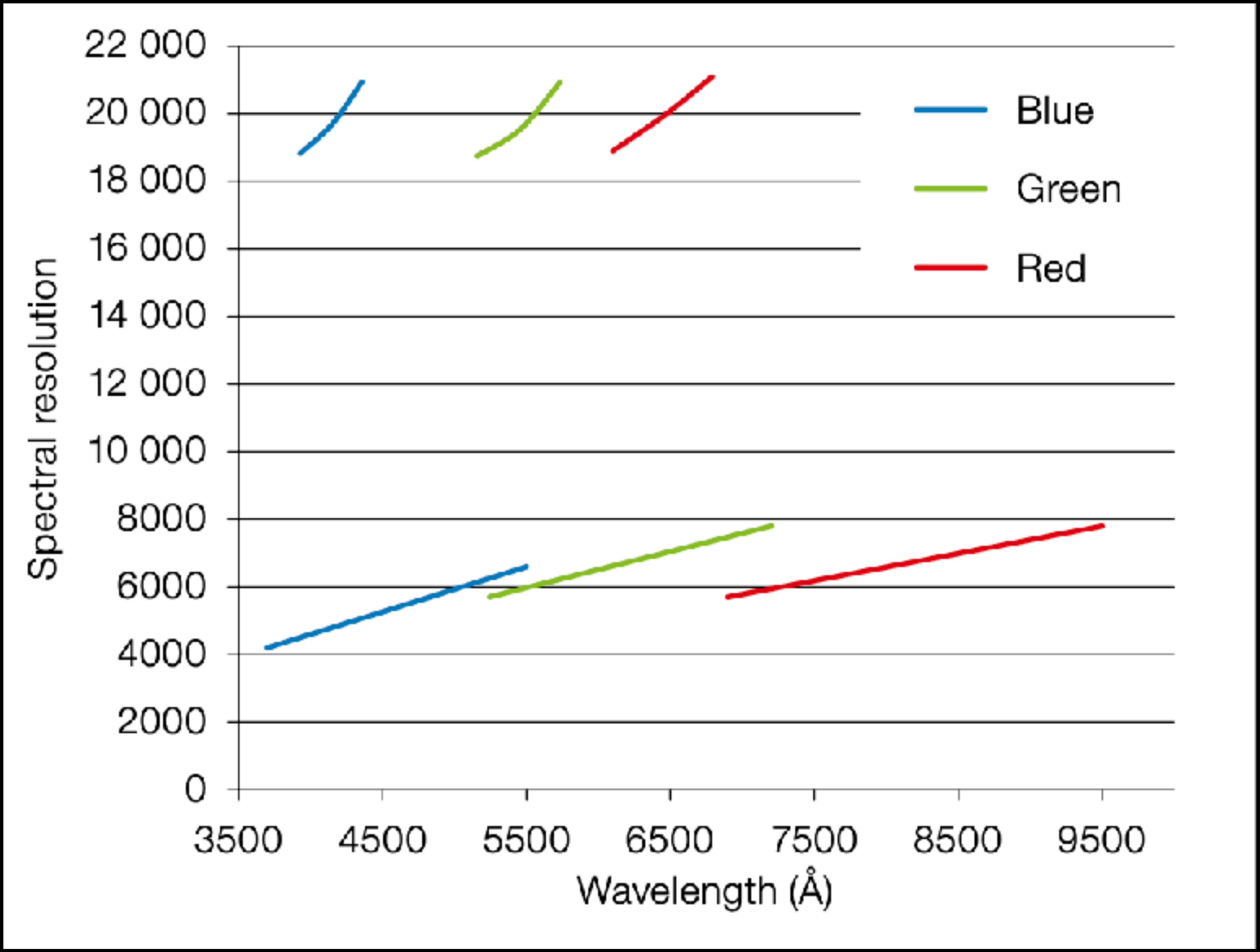
de Jong, et al. “4MOST: Project overview and information for the first call for proposal”, *The Messenger, 2019*

- Is currently being installed on the ESO VISTA 4-m telescope on Paranal
- 2400 fibres (1600 LR & 800 HR)
- 4 deg^2 field of view
- First light 2025
- 5+5 years





4MOST - wavelength coverage



de Jong (2019)

- *High-Resolution Spectrograph (812 fibres), R=20,000*
  - *Blue: 3926-4355 Å*
  - *Green: 5160-5730 Å*
  - *Red: 6060-6810 Å*
- *Low-Resolution spectrograph (1624 fibres) R=5000-7000*
  - *4000-8850 Å*

4MOST - consortium surveys

- *S1 - Milky Way Halo low-resolution survey*
  PI: Starkenburg & Irwin
- *S2 - Milky Way Halo high-resolution survey*
  PI: Christlieb
- *S3 - Milky Way Disk and bulge low-resolution survey (4MIDABLE-LR)*
  PI: Chiappini & Minchev
- *S4 - Milky Way Disk and bulge high-resolution survey (4MIDABLE-HR)*
  PI: Bensby & Bergemann
- *S5 - eRosita Galaxy cluster redshift survey*
  PI: Comparat
- *S6 - Active galactic nuclei survey*
  PI: Merloni
- *S7 - Wide area VISTA extra-galactic survey (WAVES)*
  PI: Driver & Liske
- *S8 - Cosmology redshift survey*
  PI: Kneib & Richard
- *S9 - 1001 Magellanic fields survey*
  PI: Cioni
- *S10 - The time domain extragalactic survey (TIDES)*
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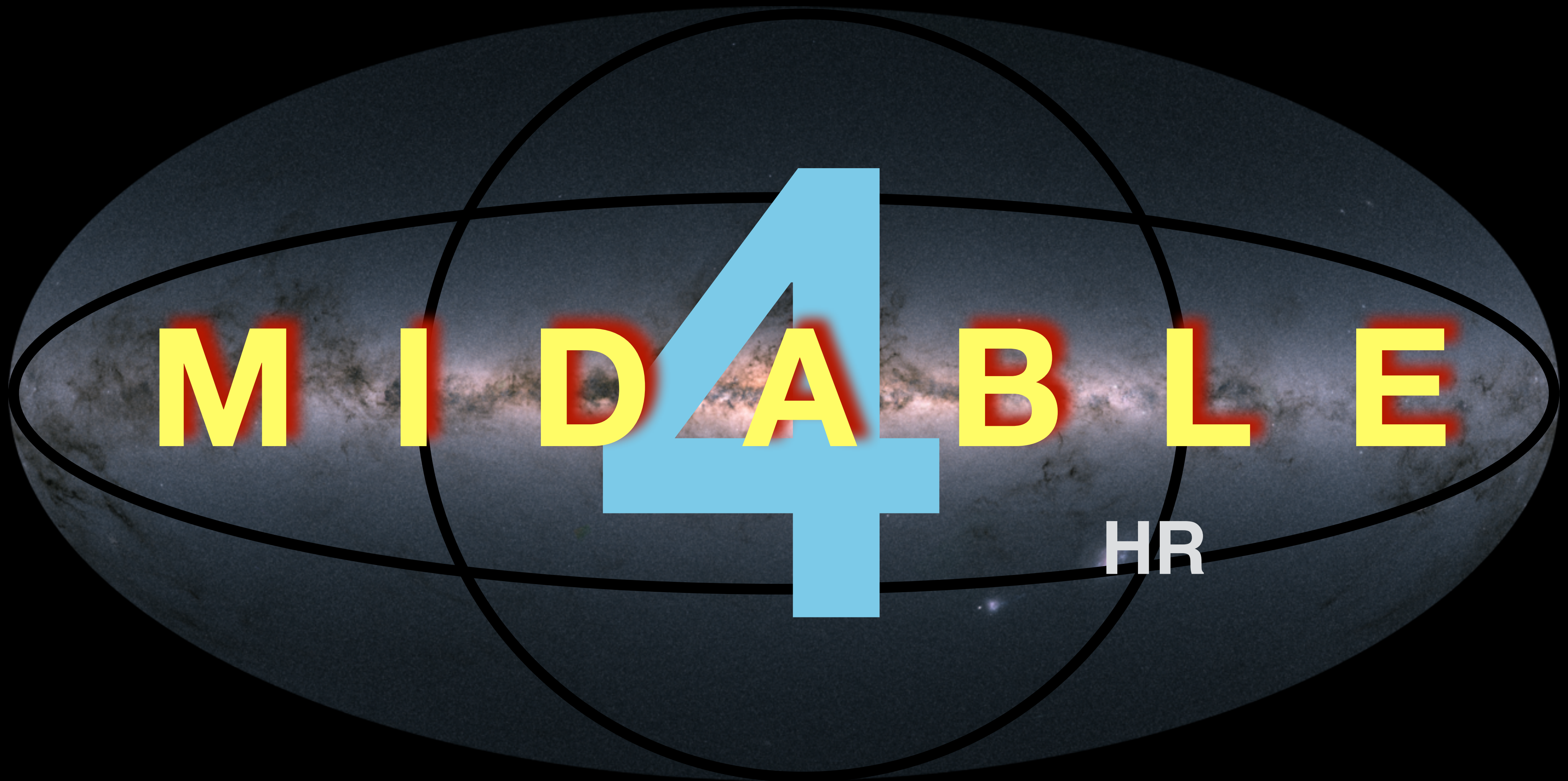
+ 15 Community surveys

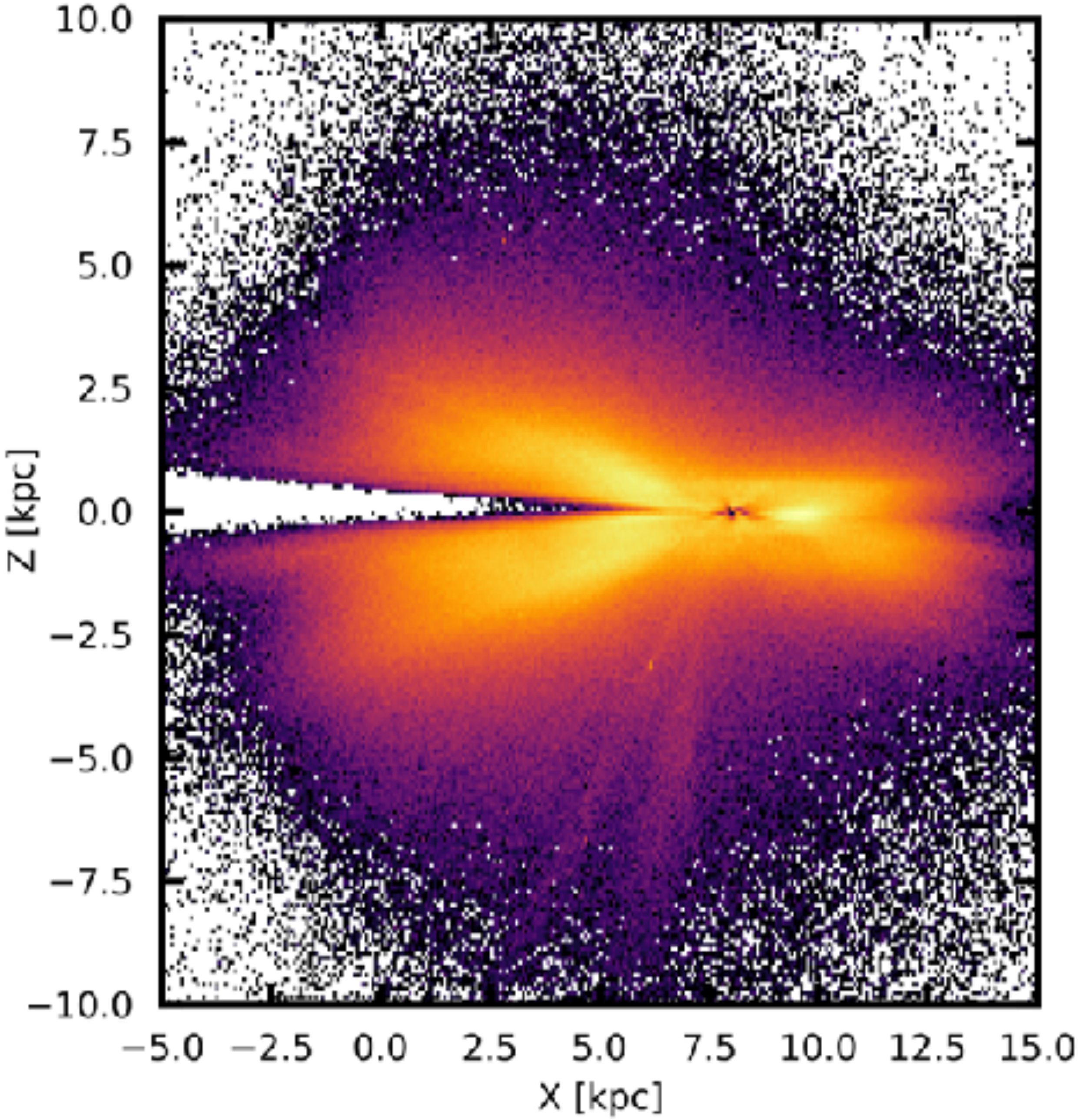


4MOST Milky Way Disk and Bulge High-Resolution Survey

co-PIs:
Thomas Bensby (Lund), Maria Bergemann (MPIA)

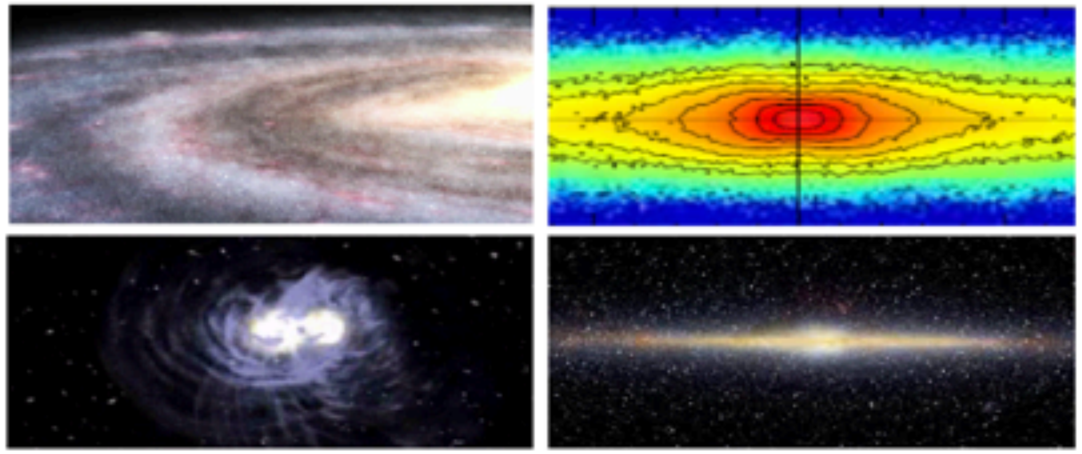
Disk & Bulge high-res survey

Bensby & Bergemann+ 2019



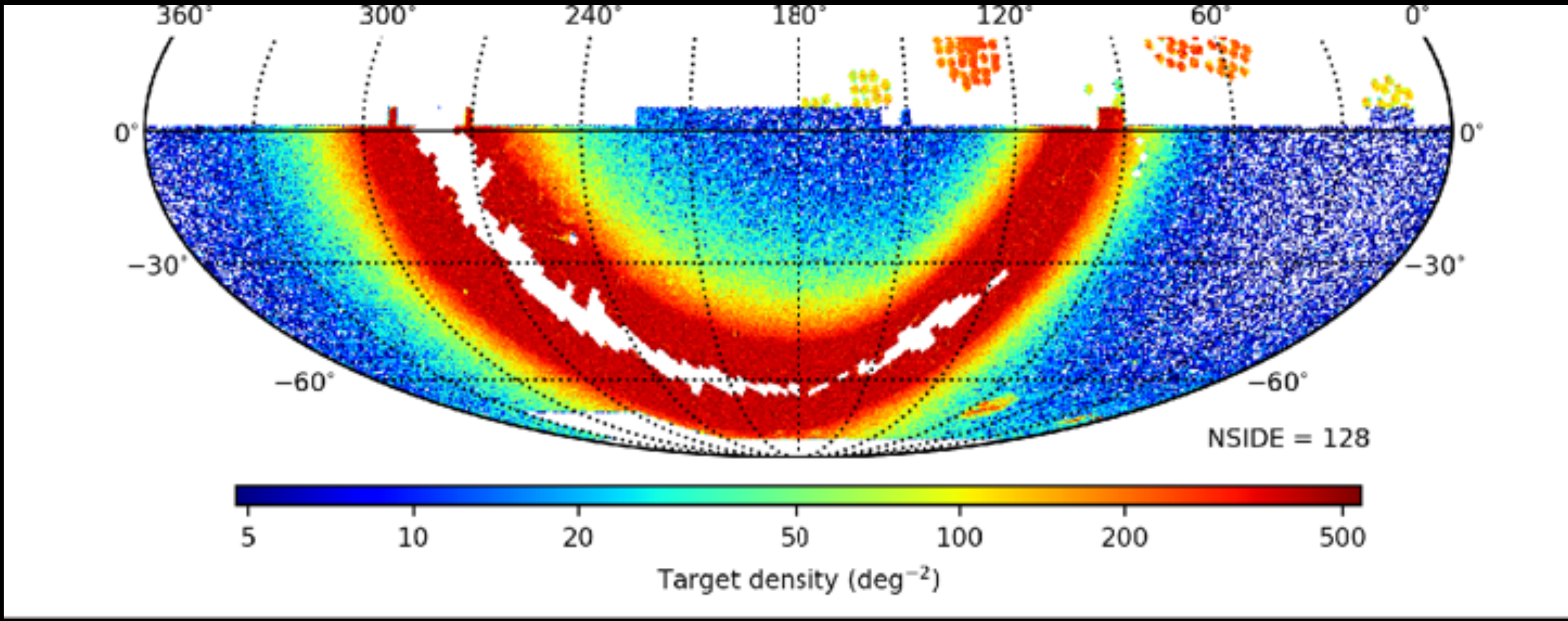
~3 million stars at R = 20 000

- Galactic discs: radial migration, mergers, oscillations
- Classical or pseudo-bulge or both
- Stellar physics

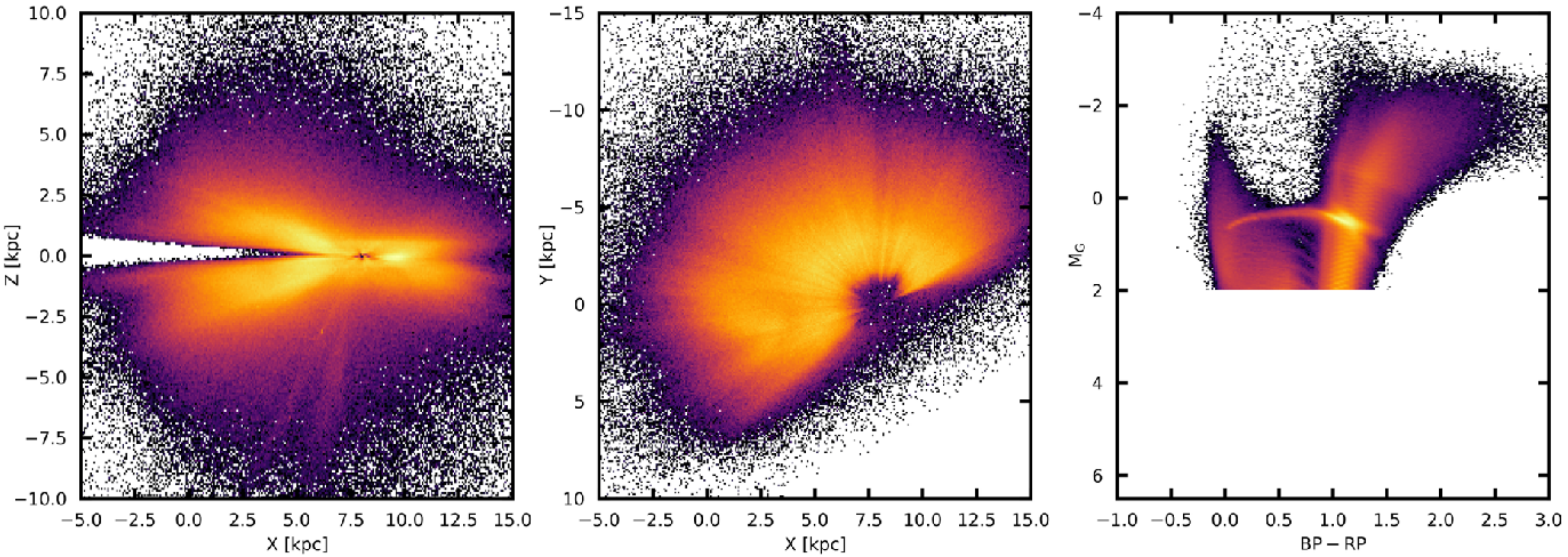


***Science applications**: stellar physics, dark matter distribution, spiral arm dynamics, stellar siblings, mass function, exoplanet hosts, star cluster evolution and dissolution, history of chemical elements, …*

Main selection



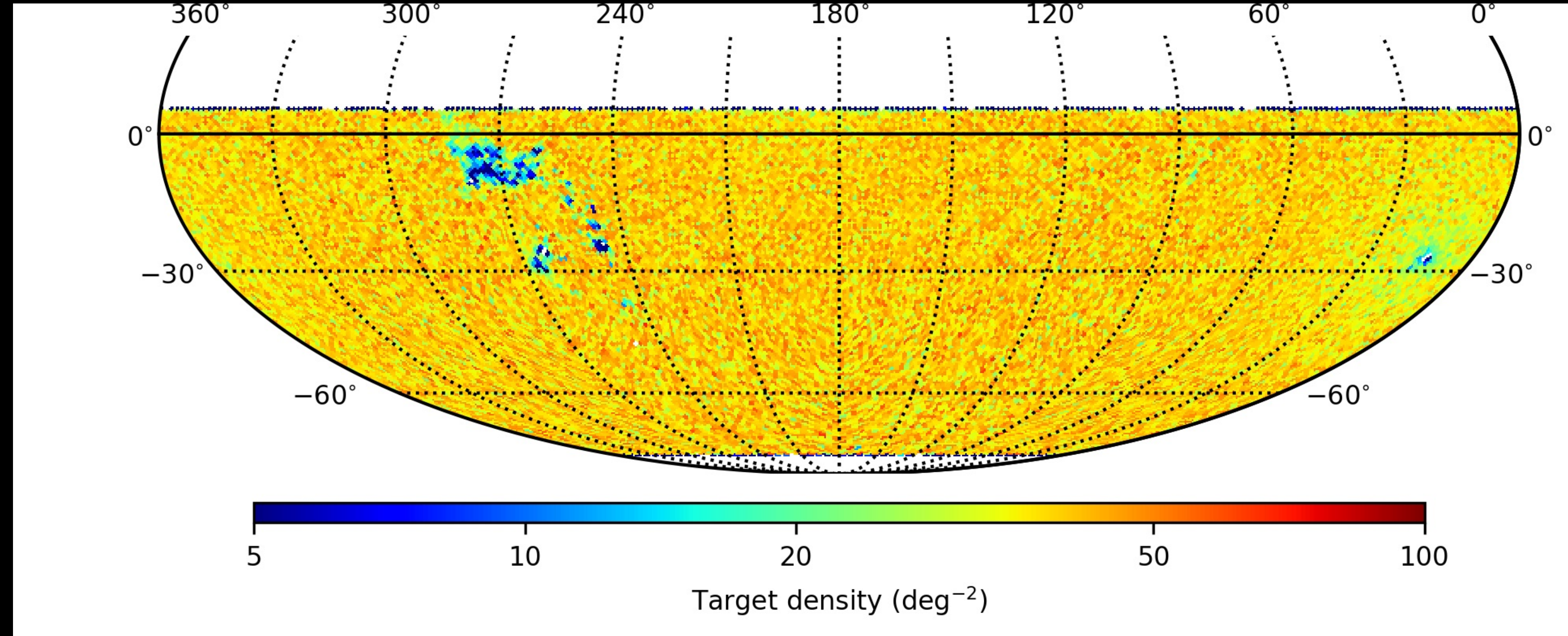
Spectra of >3 million stars with a simple and even selection based on Gaia in 3 Galactic quadrants, sampling a volume of > 10 kpc



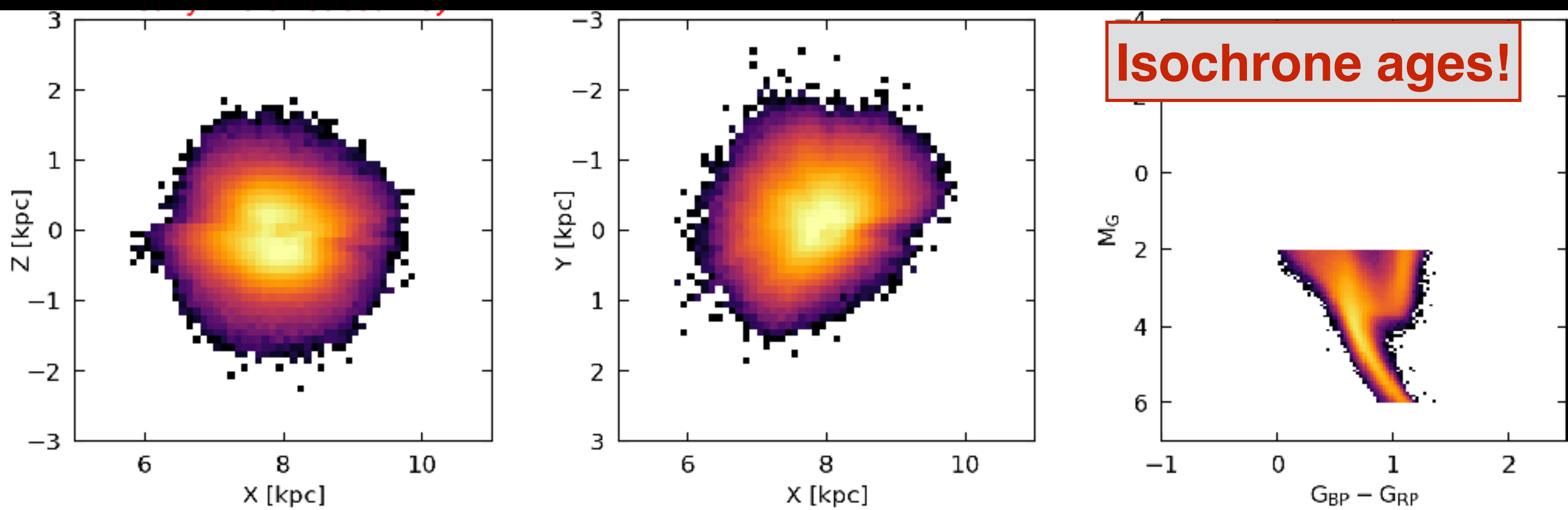
all evolutionary stages, M_G cut to avoid K dwarfs

Z-disk

Neutron-capture nucleosynthesis and enrichment cycle in the Galaxy through analysis of light, s-,r- process abundance patterns in the local volume



Li, C, N, O, Mg, Si, Ca, Sc, Ti, V, Cr, Mn, Ni, Co, Cu, Zn, light s- (Sr, Y, Zr), heavy s- (Ba, La, Ce, Pr, Nd), and r-process elements (Sm, Eu, Gd)



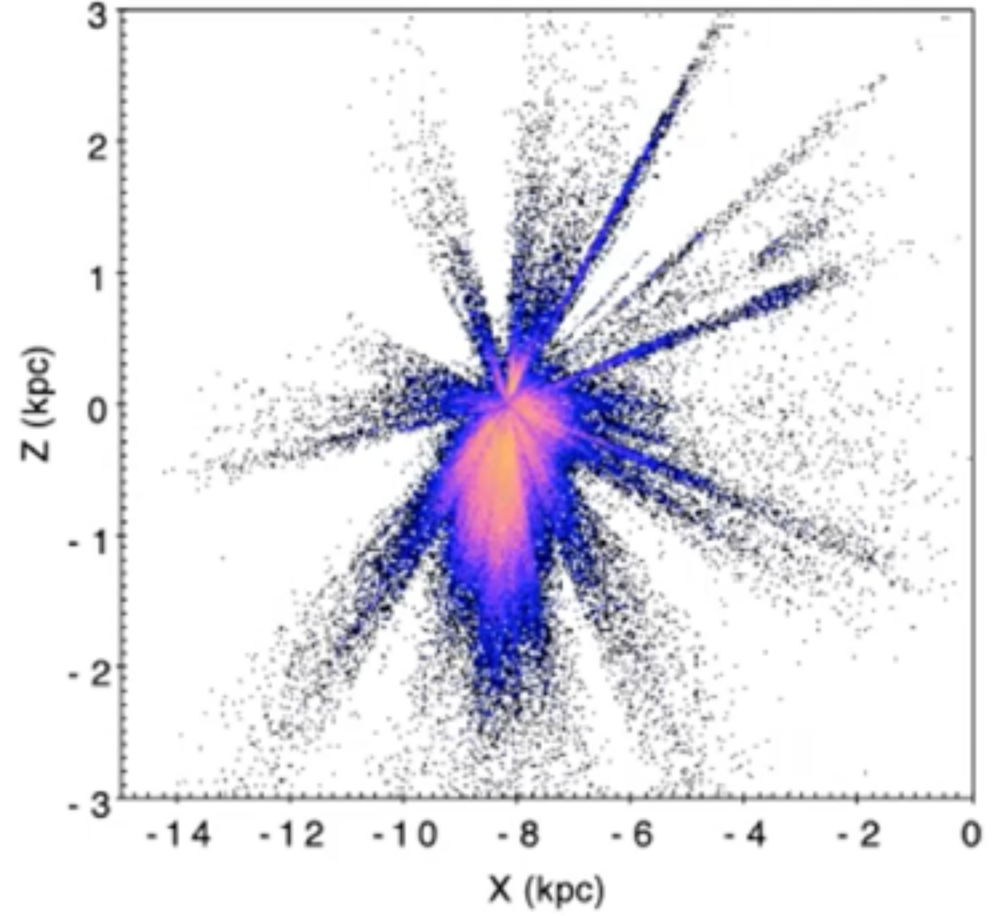
~0.8 million FGK spectra at SNR ~ 250 / Å in the blue

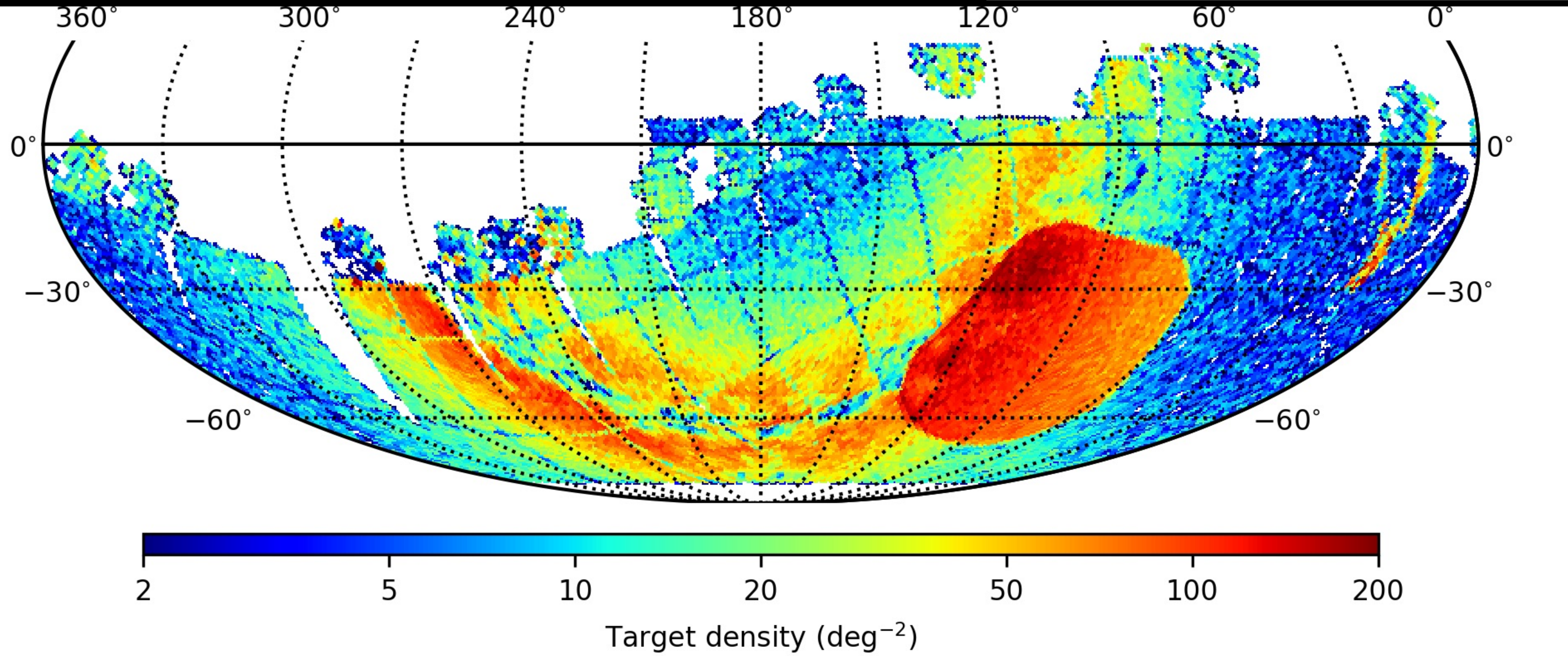
Asteroseismic samples

585 000 asteroseismic targets

– selection based on Gaia, K2 and TESS, PLATO
– main-sequence, subgiants, red giants, red clump;

global seismic parameters (vmax, Δv)
=> radii, masses, ages

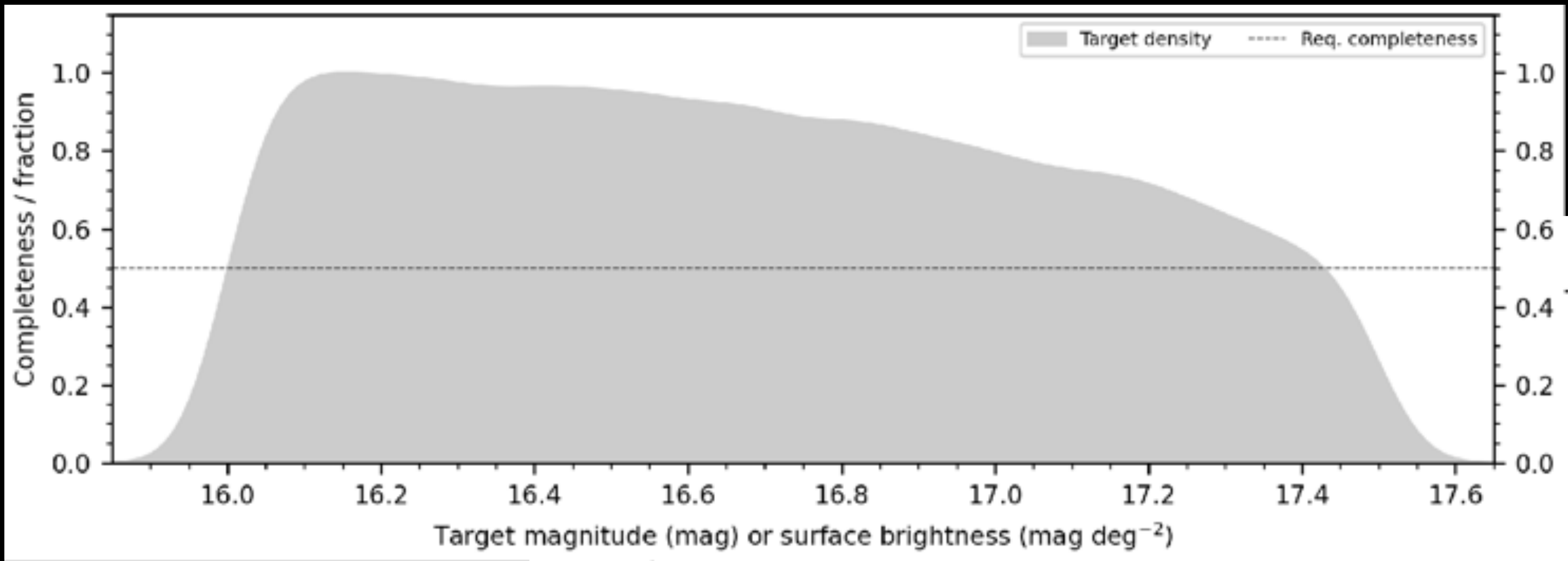


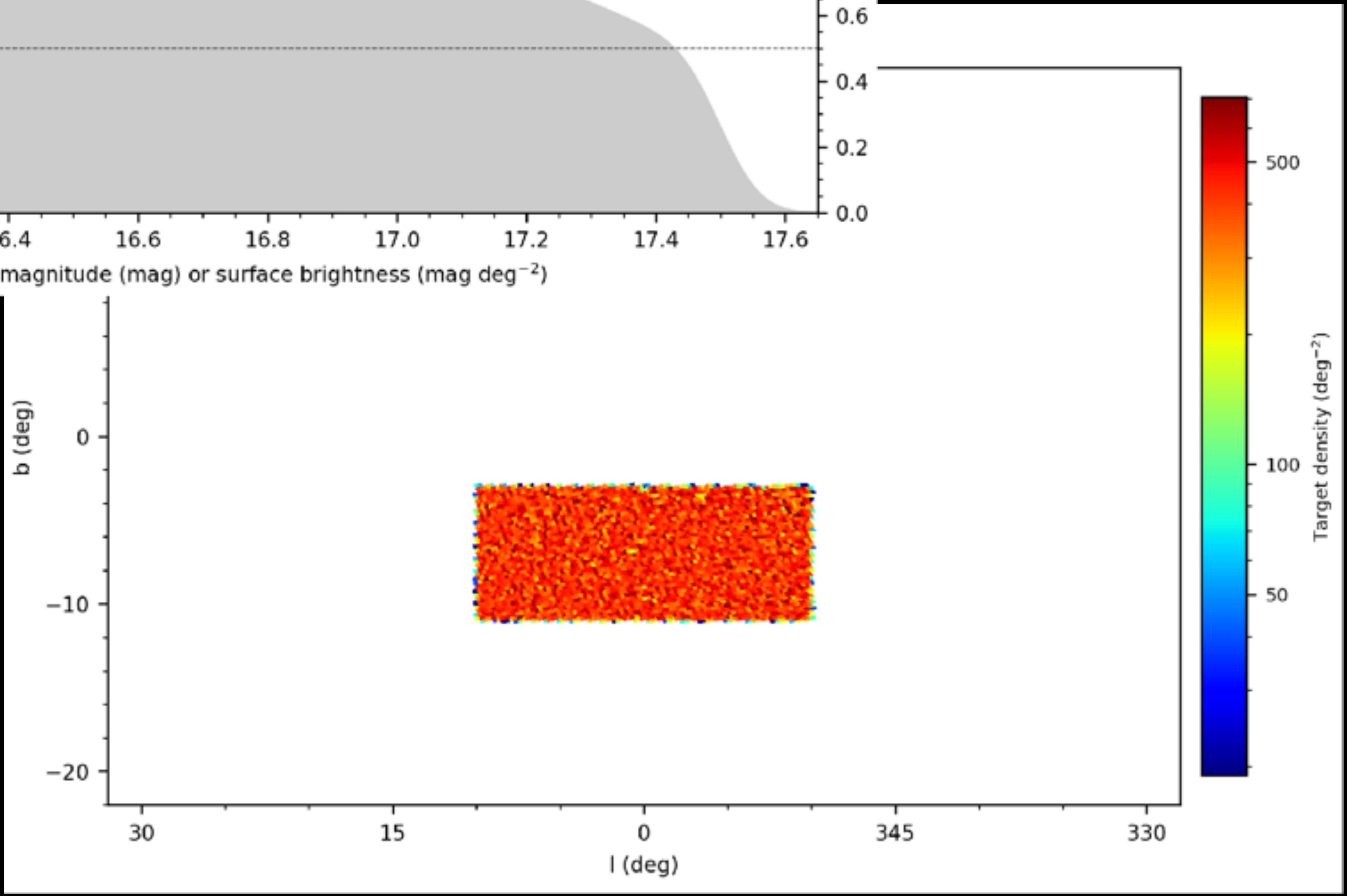


Deep Bulge

68 000 targets

global seismic parameters (νmax, Δν)
=> radii, masses, ages



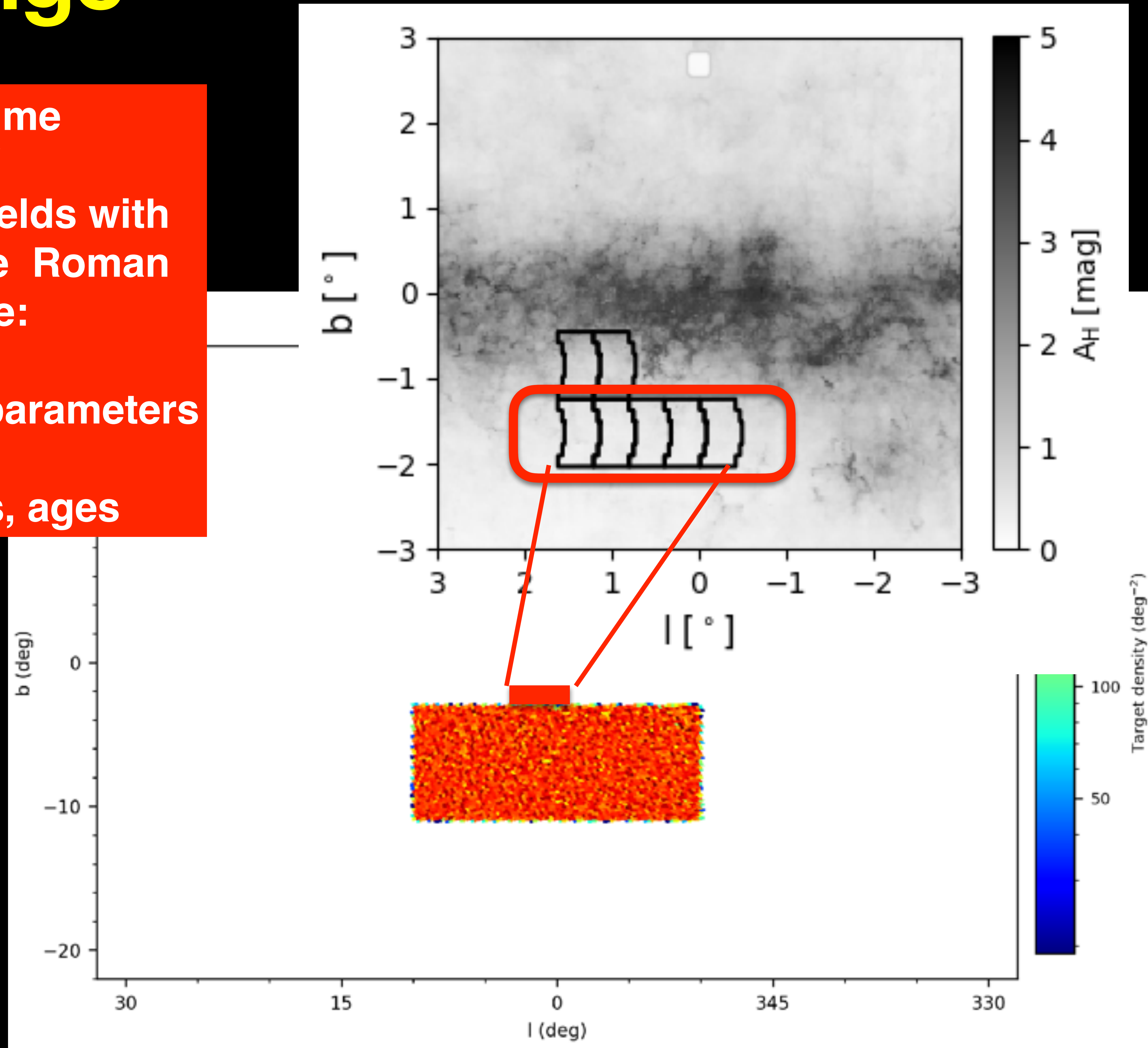


Deep Bulge

68 000 targets + 10000 targets

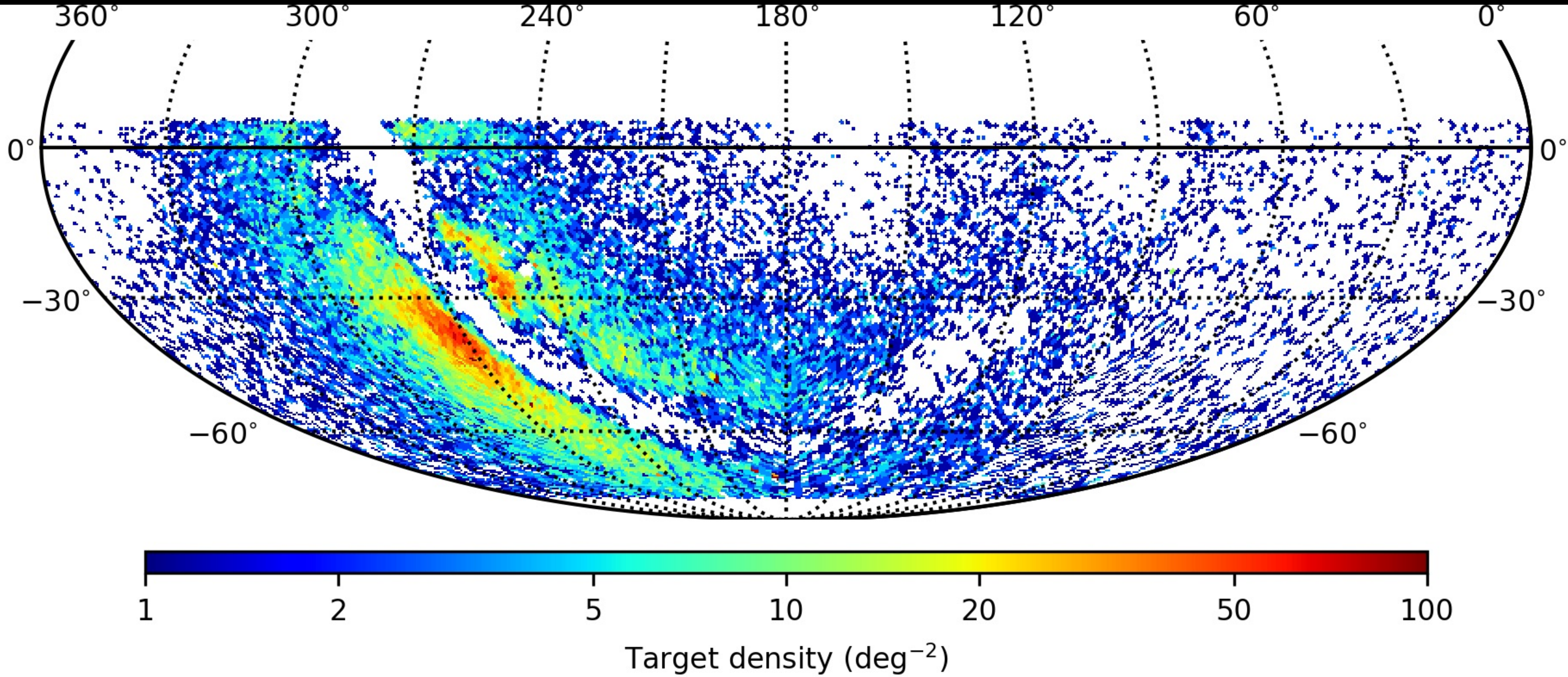
Galactic bulge time domain survey / asteroseismic fields with the Nancy Grace Roman Space Telescope:

global seismic parameters (νmax, Δν)
=> radii, masses, ages

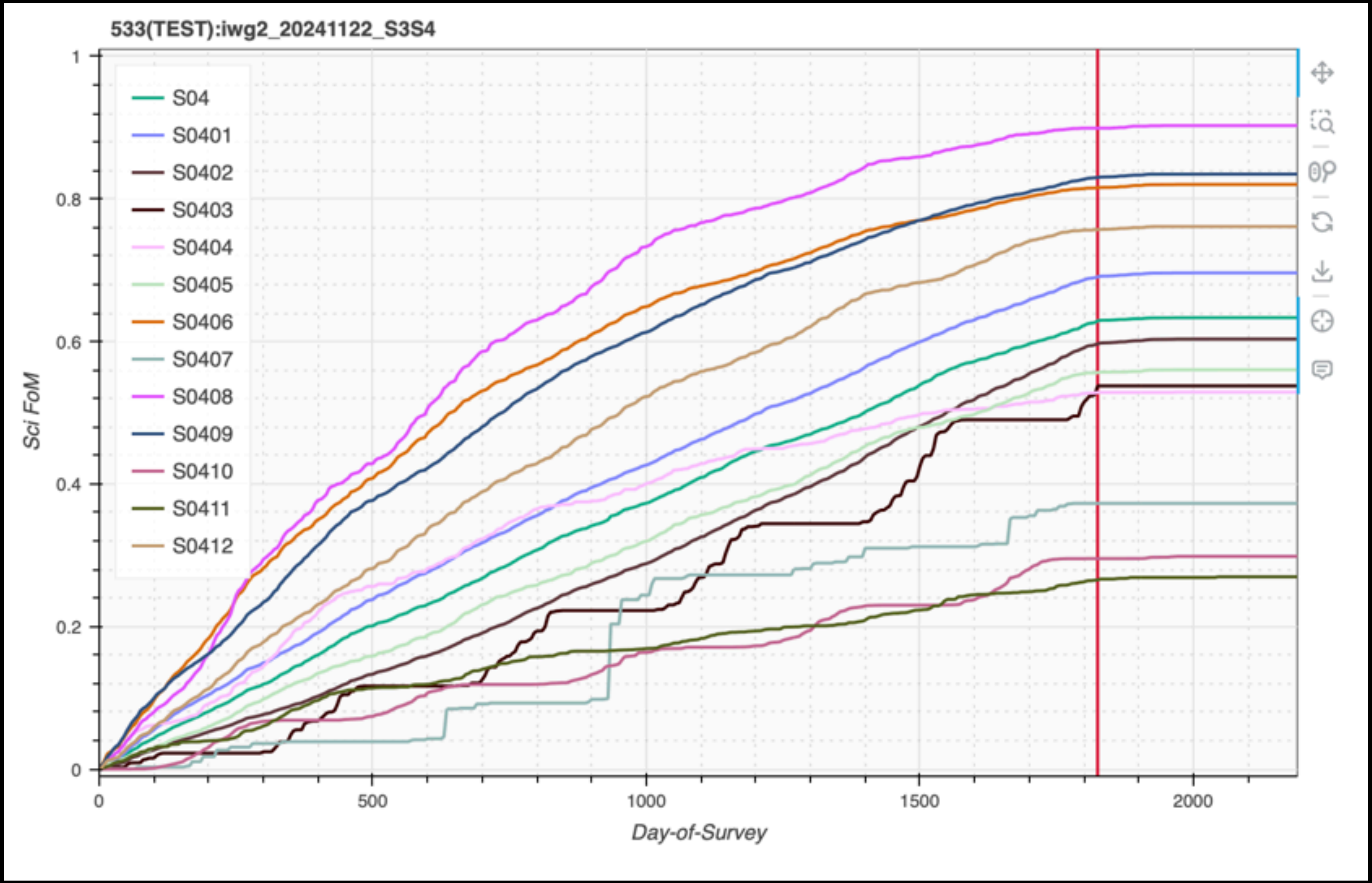


Metal-poor disk and bulge

≈ 70 000 metal-weak candidates
[Fe/H]<-1.5, based on Andrae et al. (2022) all-sky Gaia Bp/Rp analysis
most metal-poor part of the bulge (Rix et al. 2022)

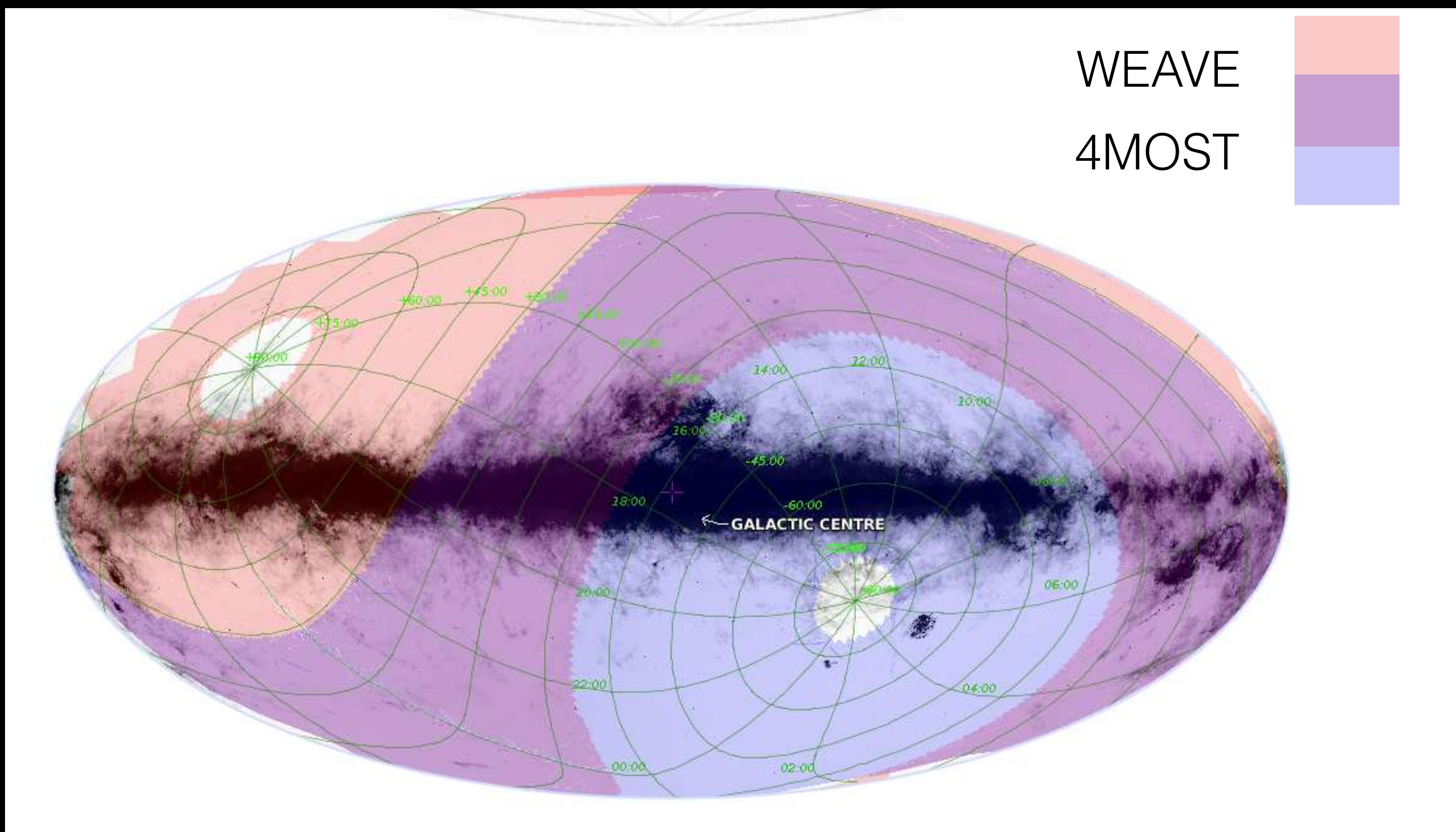


Will it work?



533(TEST):iwg2_20241122_S3S4
S04
S0401
S0402
S0403
S0404
S0405
S0406
S0407
S0408
S0409
S0410
S0411
S0412
Sci FoM
Day-of-Survey
0
0.2
0.4
0.6
0.8
1
0
500
1000
1500
2000

4MOST vs WEAVE



WEAVE:
outer disk,
anti-centre

4MOST:
inner disk, bulge

Complementary, so it is important to have cross-calibration fields

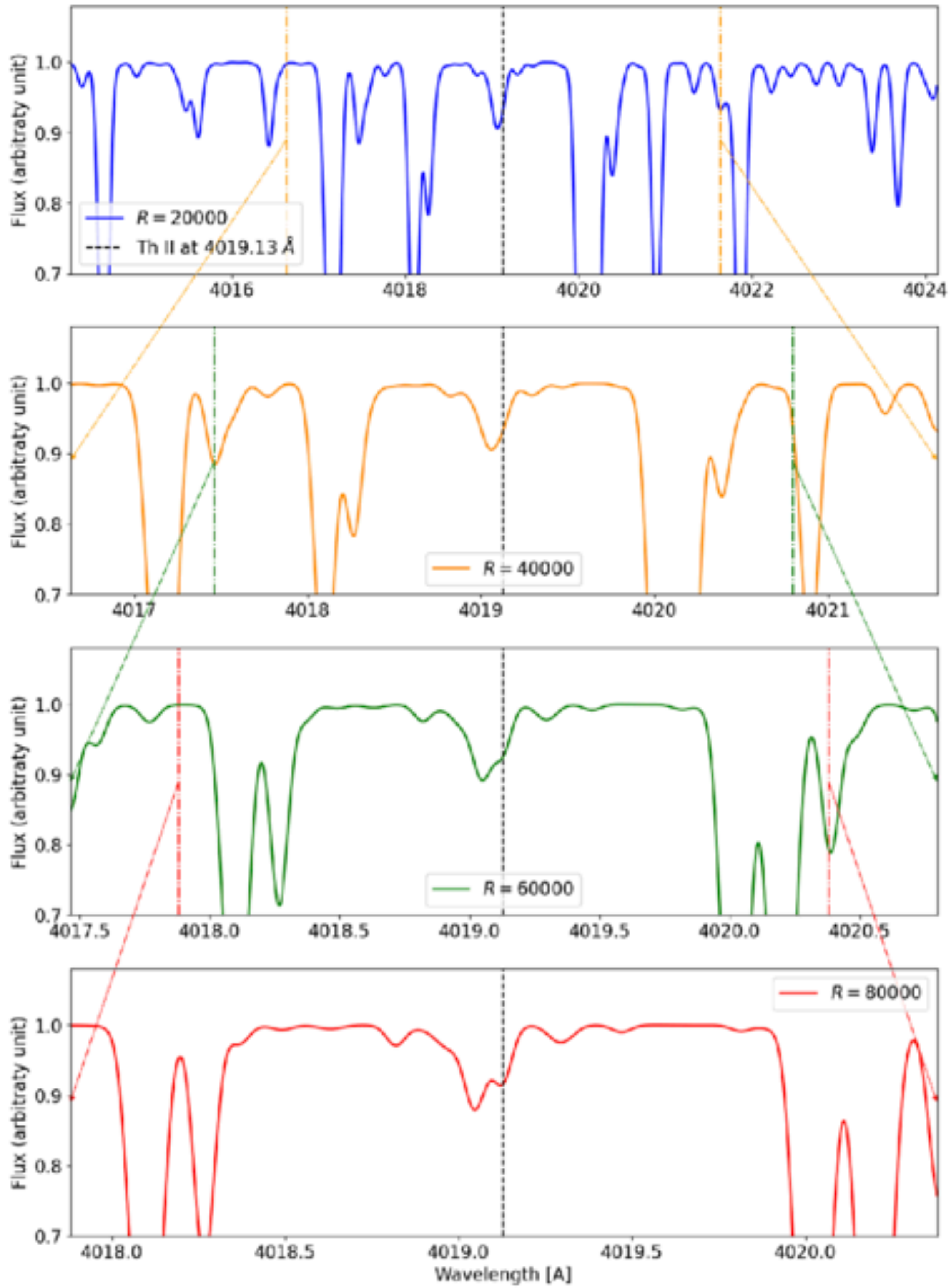
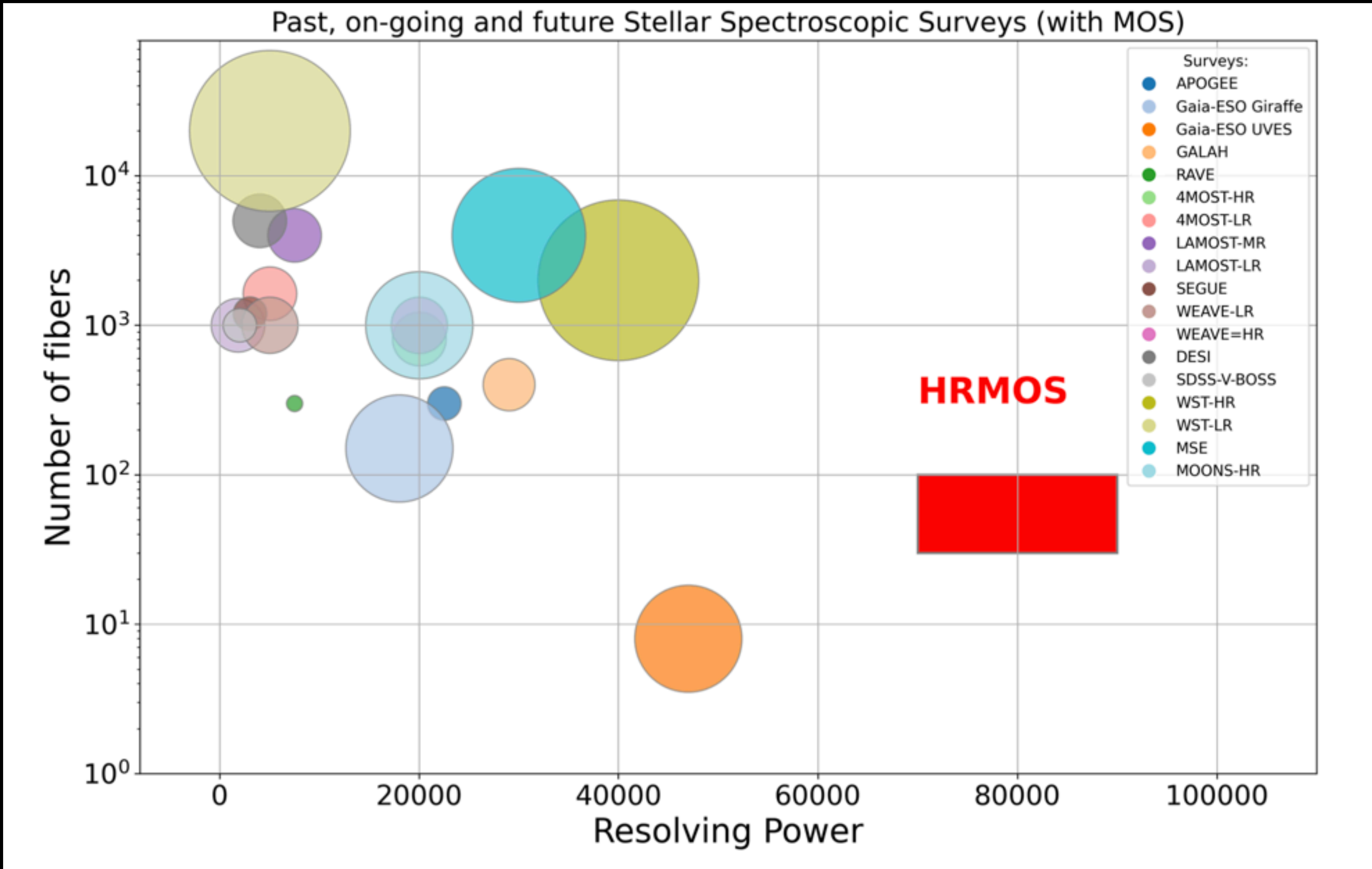


Figure 2: Synthetic spectrum of a giant star (4200 K, 2.5, -2.5) at four different resolutions. In each panel, a zoomed-in portion of the wavelength range of the corresponding upper panel is shown. The vertical dashed line indicates the Th II line at 4019.13 Å, which can be separated at $R > 60\,0000$.

Magrini, Bensby, et al. (2024)



Magrini, Bensby, et al. (2024)

First light next year!