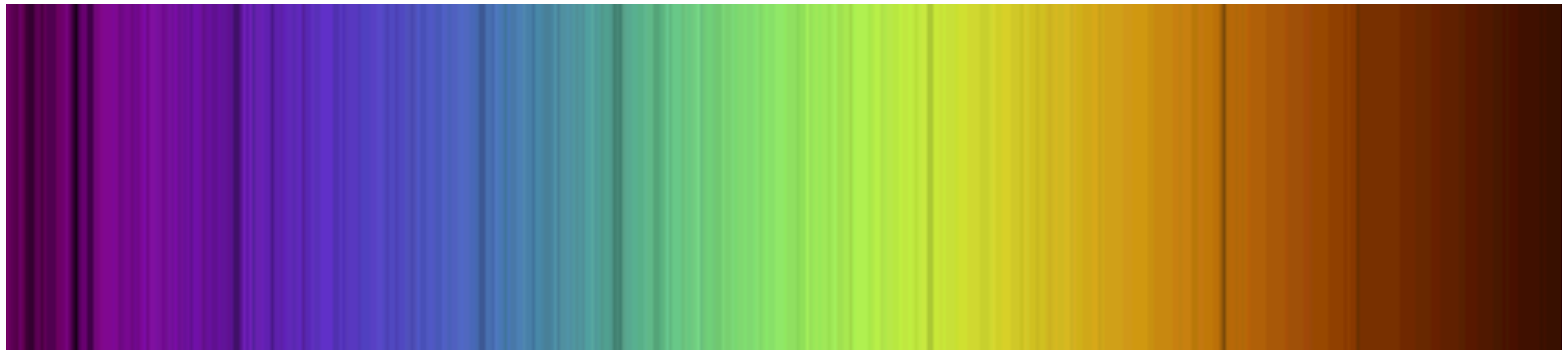
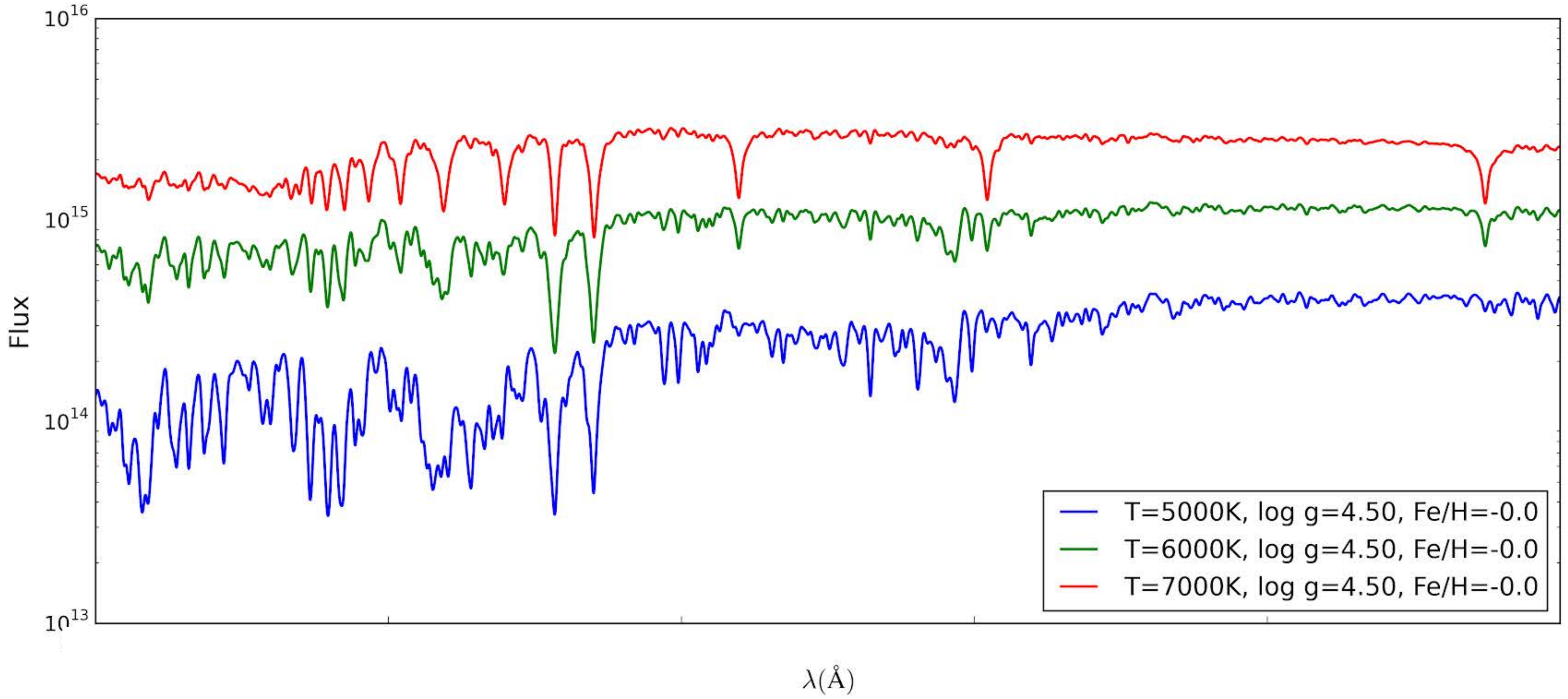
DIS Galactic Archaeology module

Lecture 5: How to design an astronomical survey?

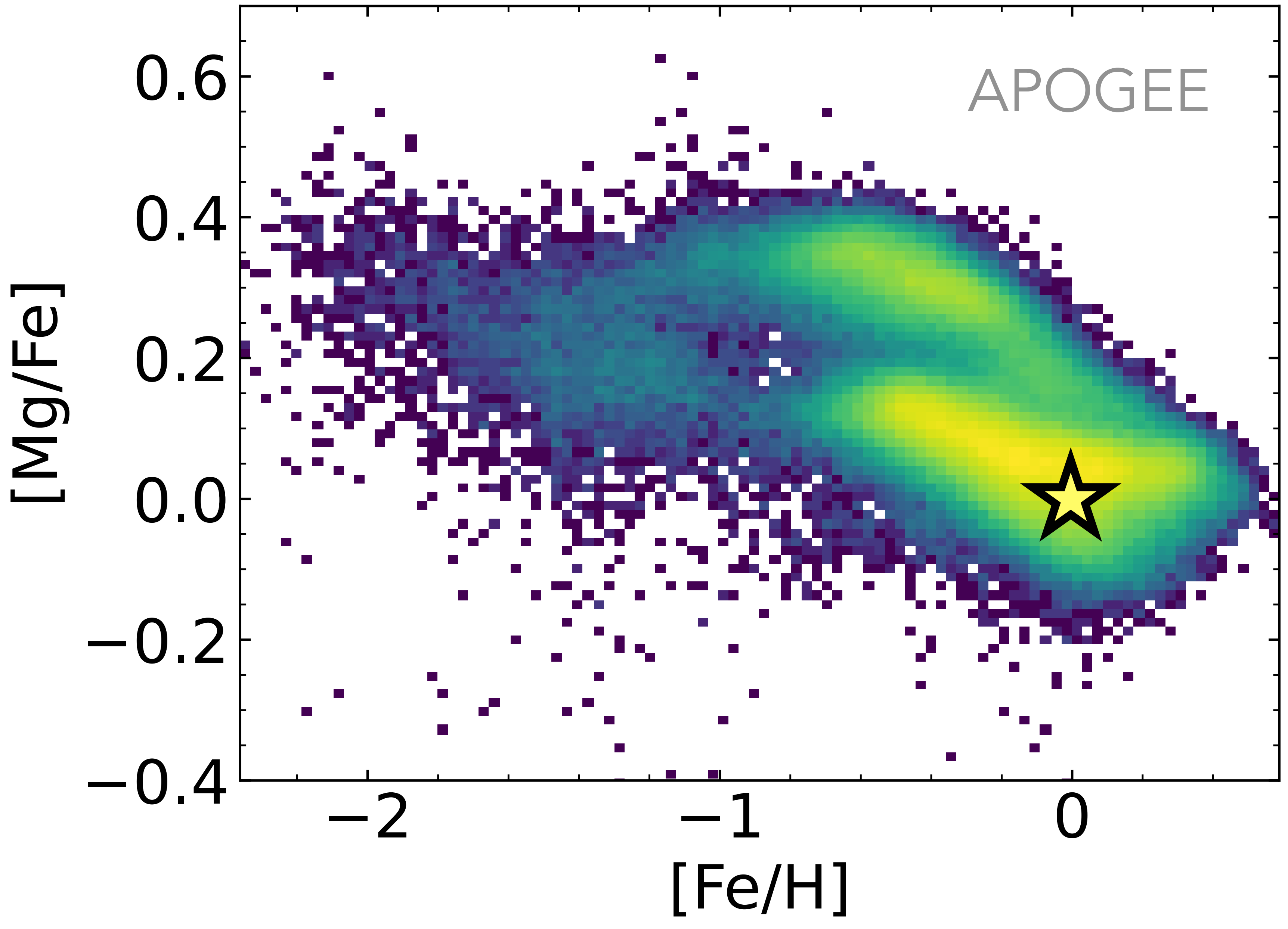
Dr Anke Ardern-Arentsen

Recap from previous lecture



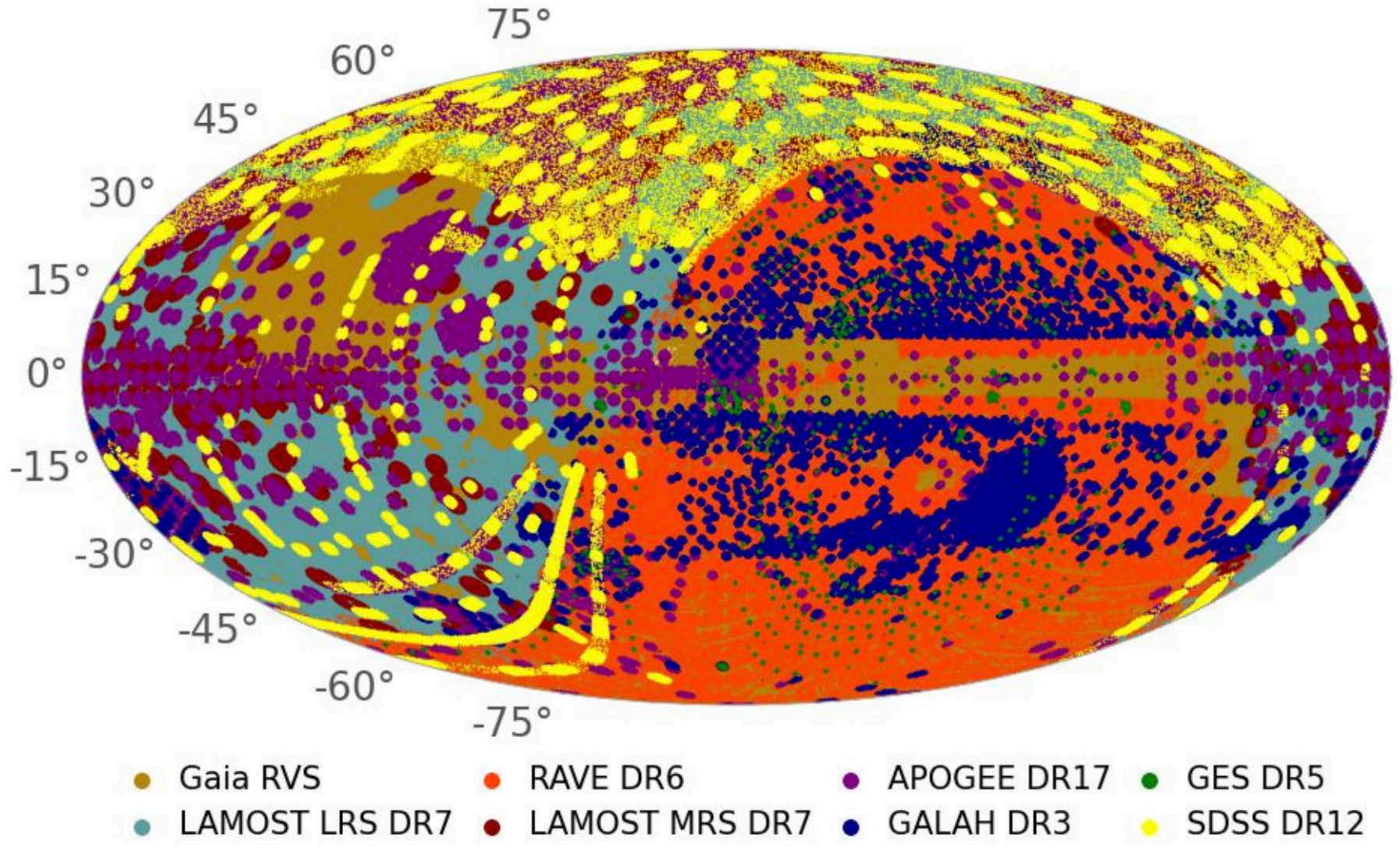


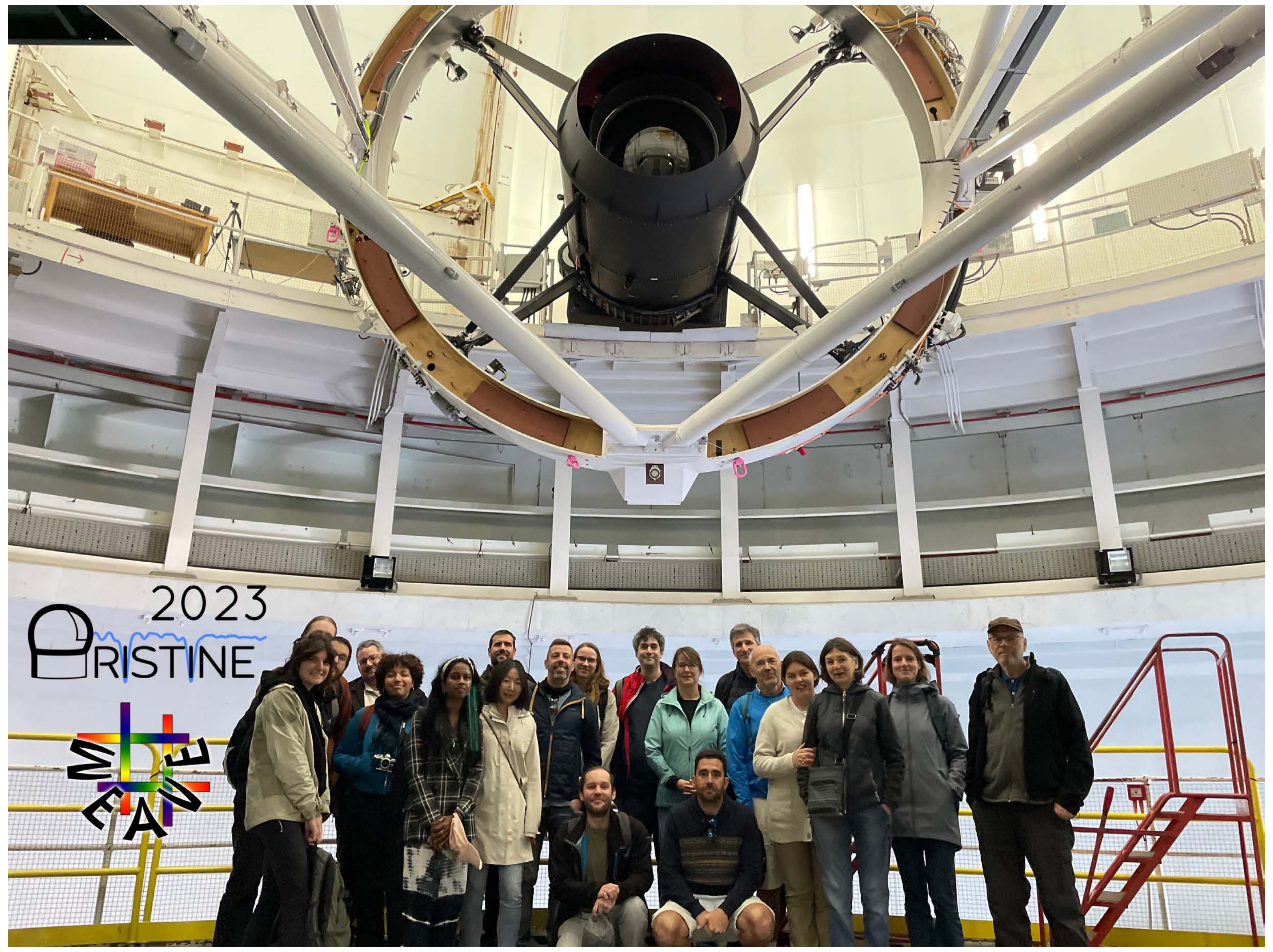
Any questions so far?



In this lecture

- ➤ Telescopes
- ➤ PI proposals/small surveys: the typical observing cycle
- ➤ Large surveys

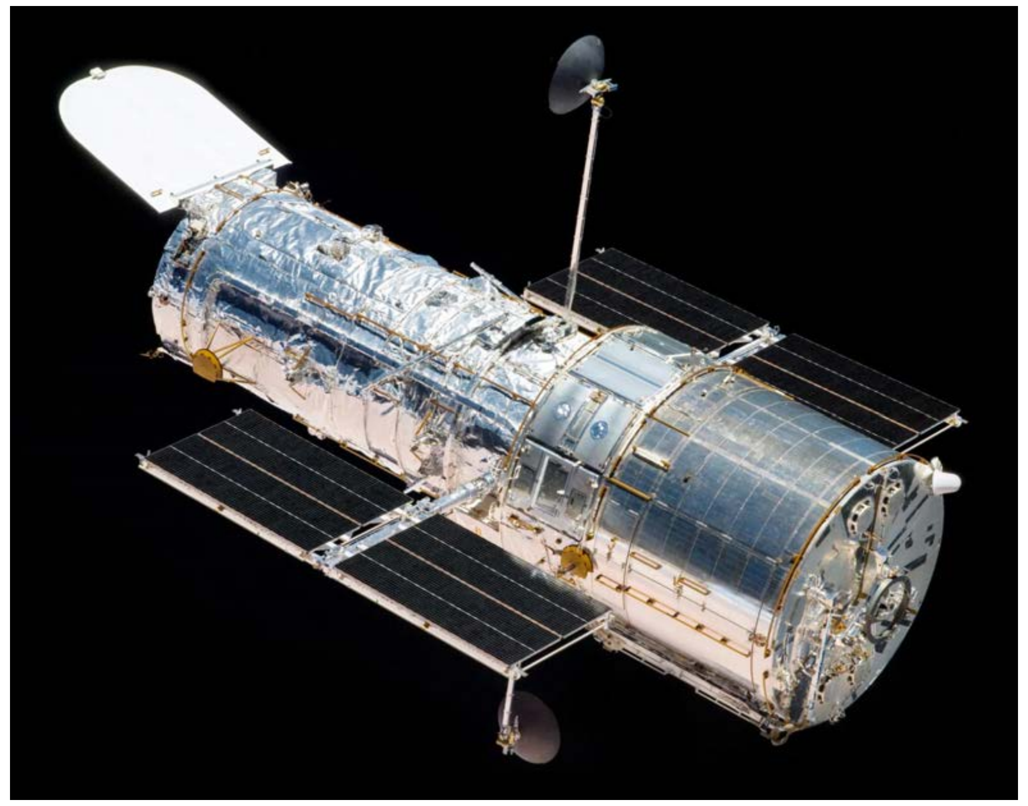




Telescopes

INT, La Palma (2.5m)

Hubble, space (2.4m)



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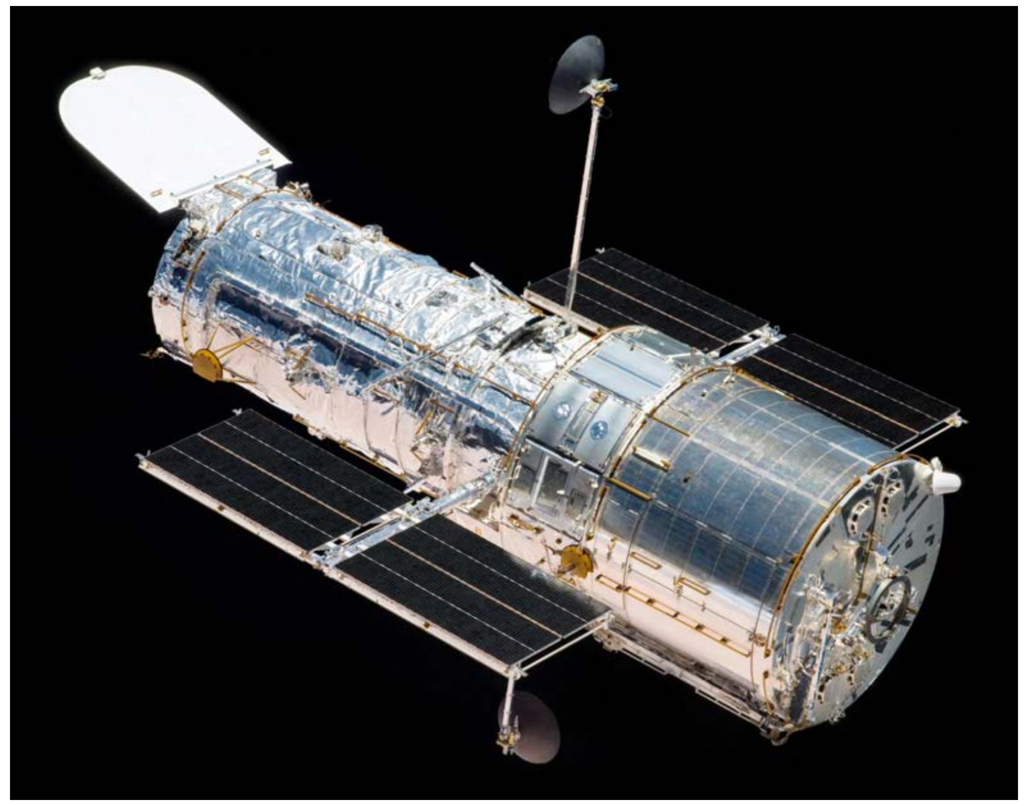

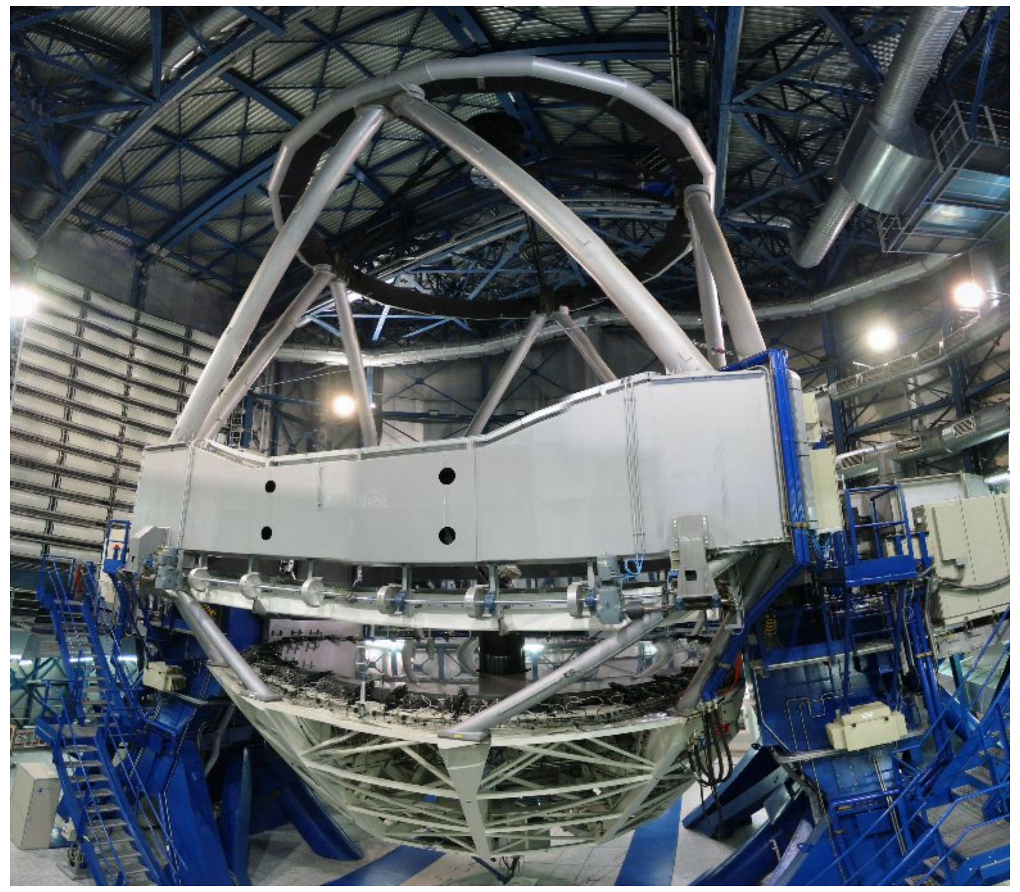

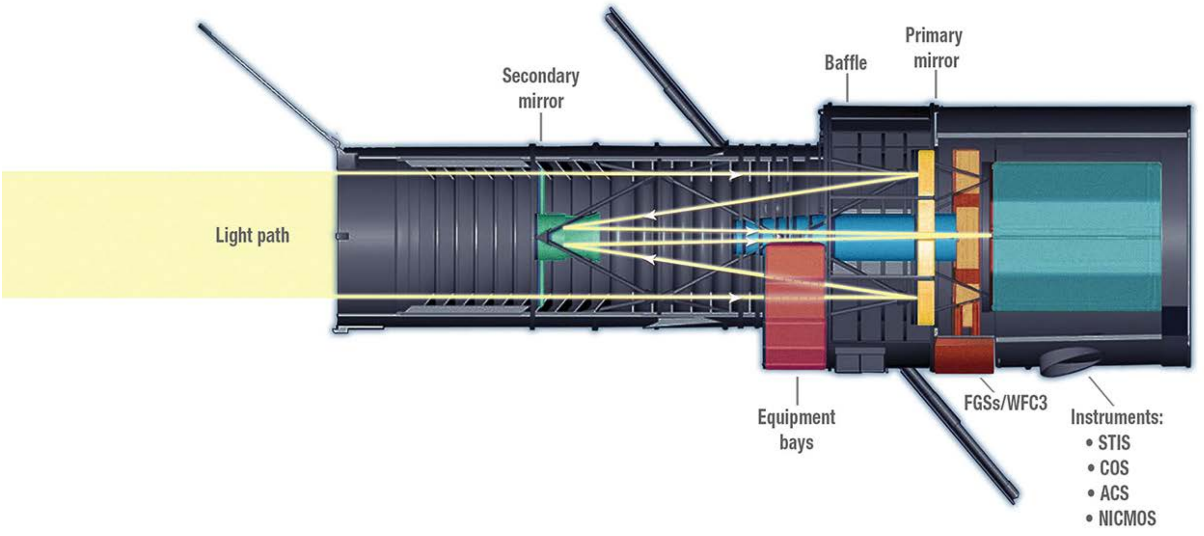

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1. Lager field of view
2. Better resolution
3. Collecting more light

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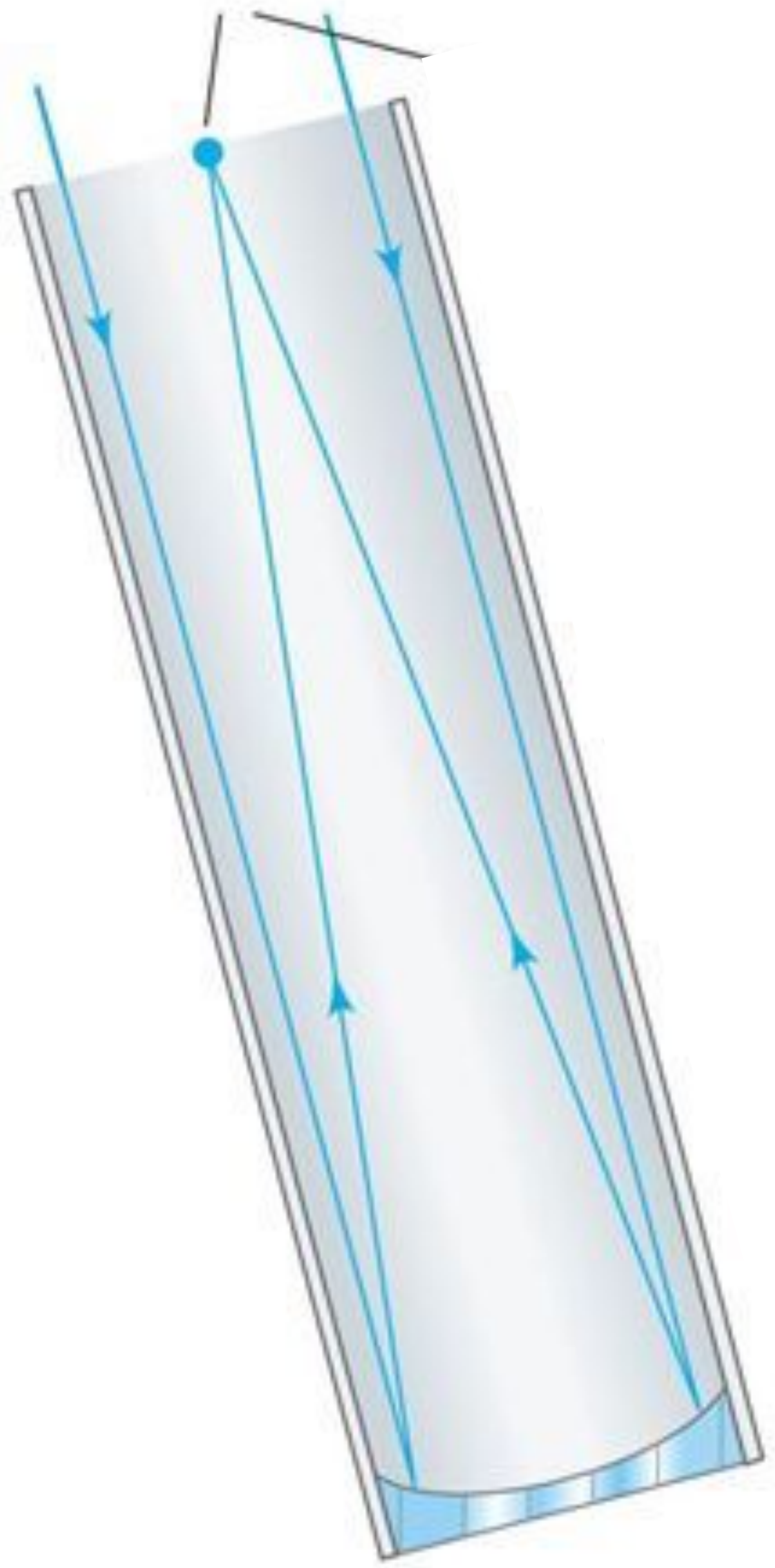
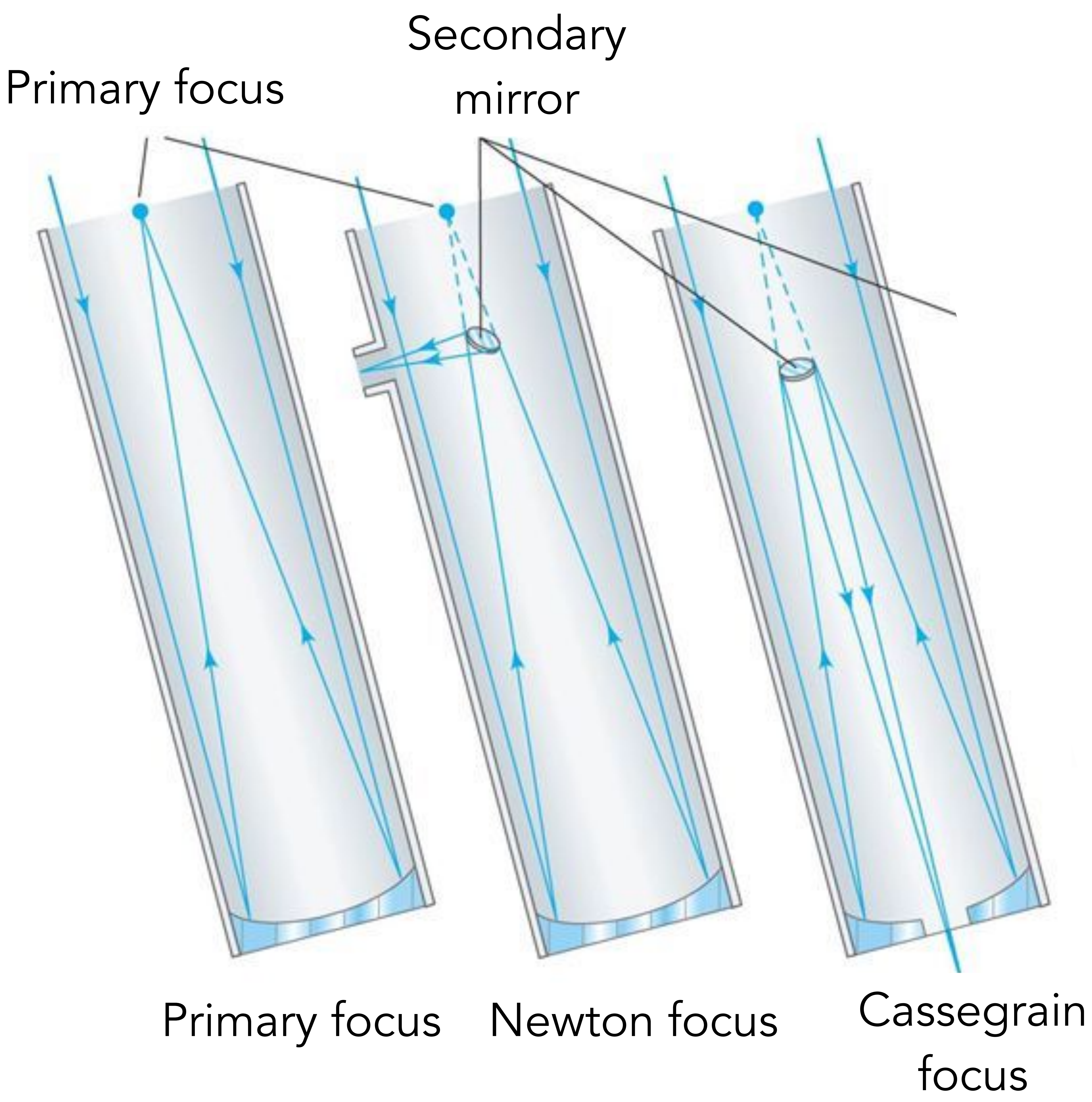
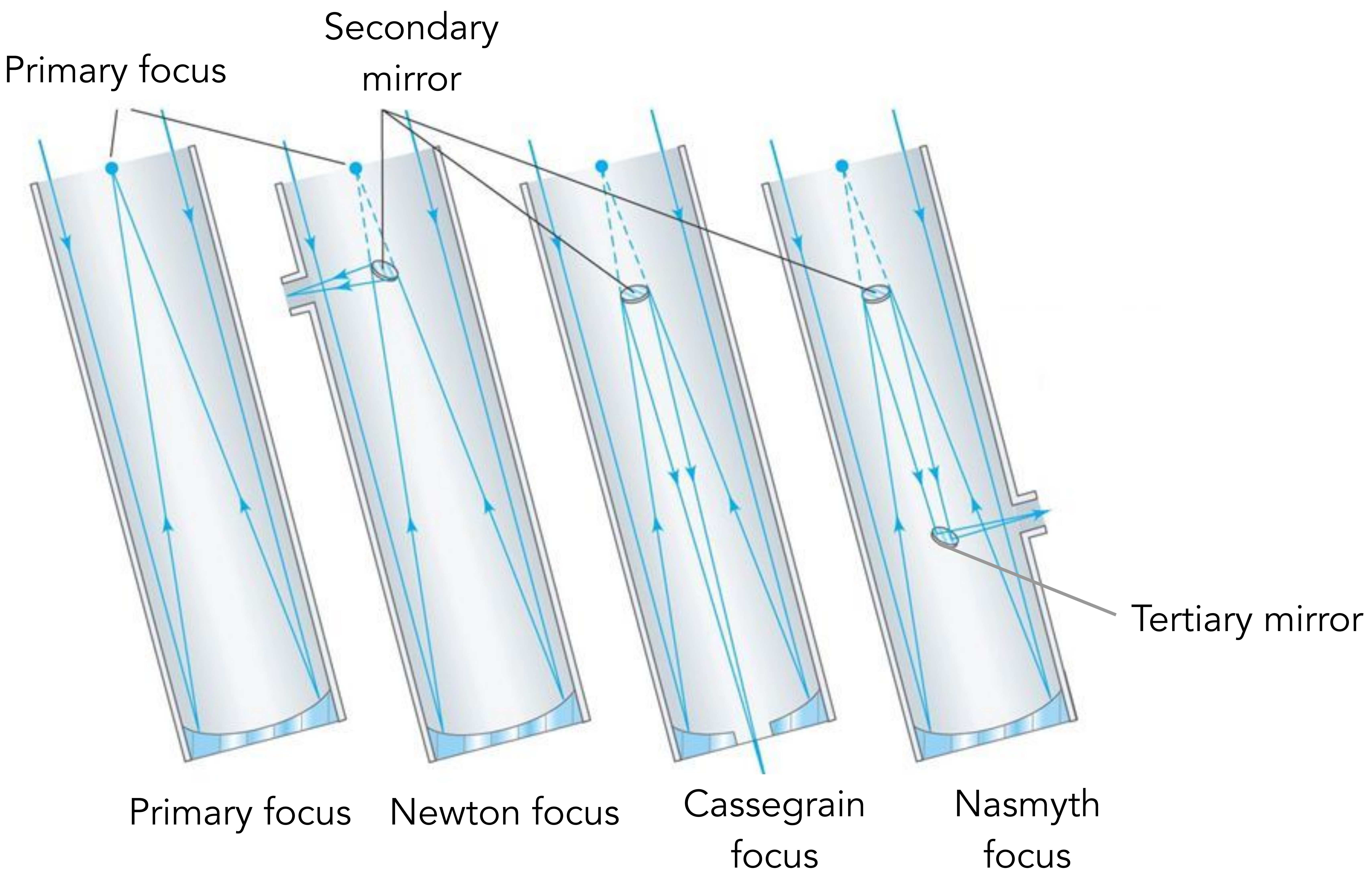
Primary focus



Primary focus


Secondary
mirror
Primary focus
Primary focus
Newton focus

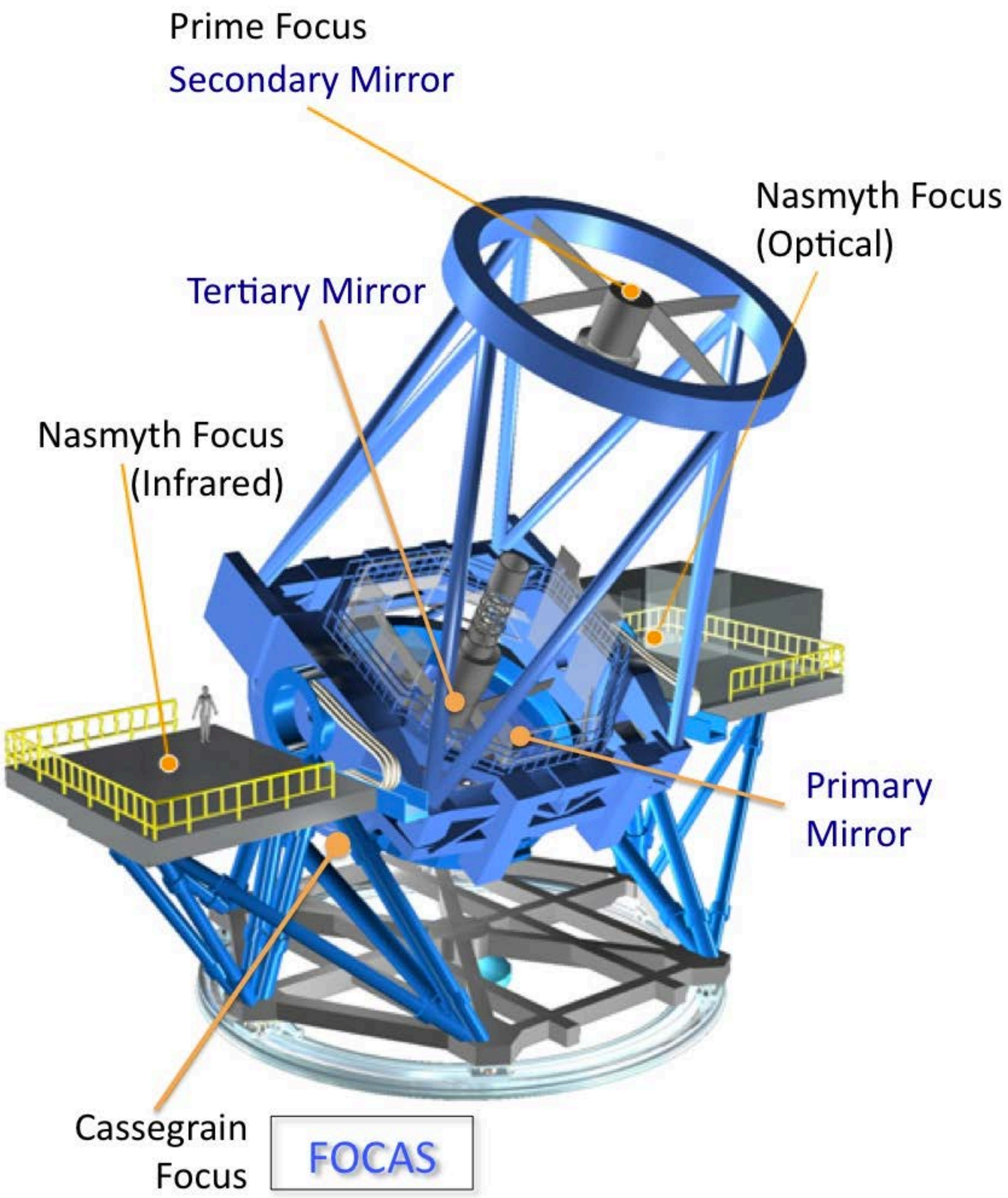

Secondary
mirror
Primary focus
Primary focus
Newton focus
Cassegrain
focus


Secondary mirror
Primary focus
Tertiary mirror
Primary focus
Newton focus
Cassegrain focus
Nasmyth focus

Typical large telescope

Each telescope can have more than one instrument, in the different focus positions

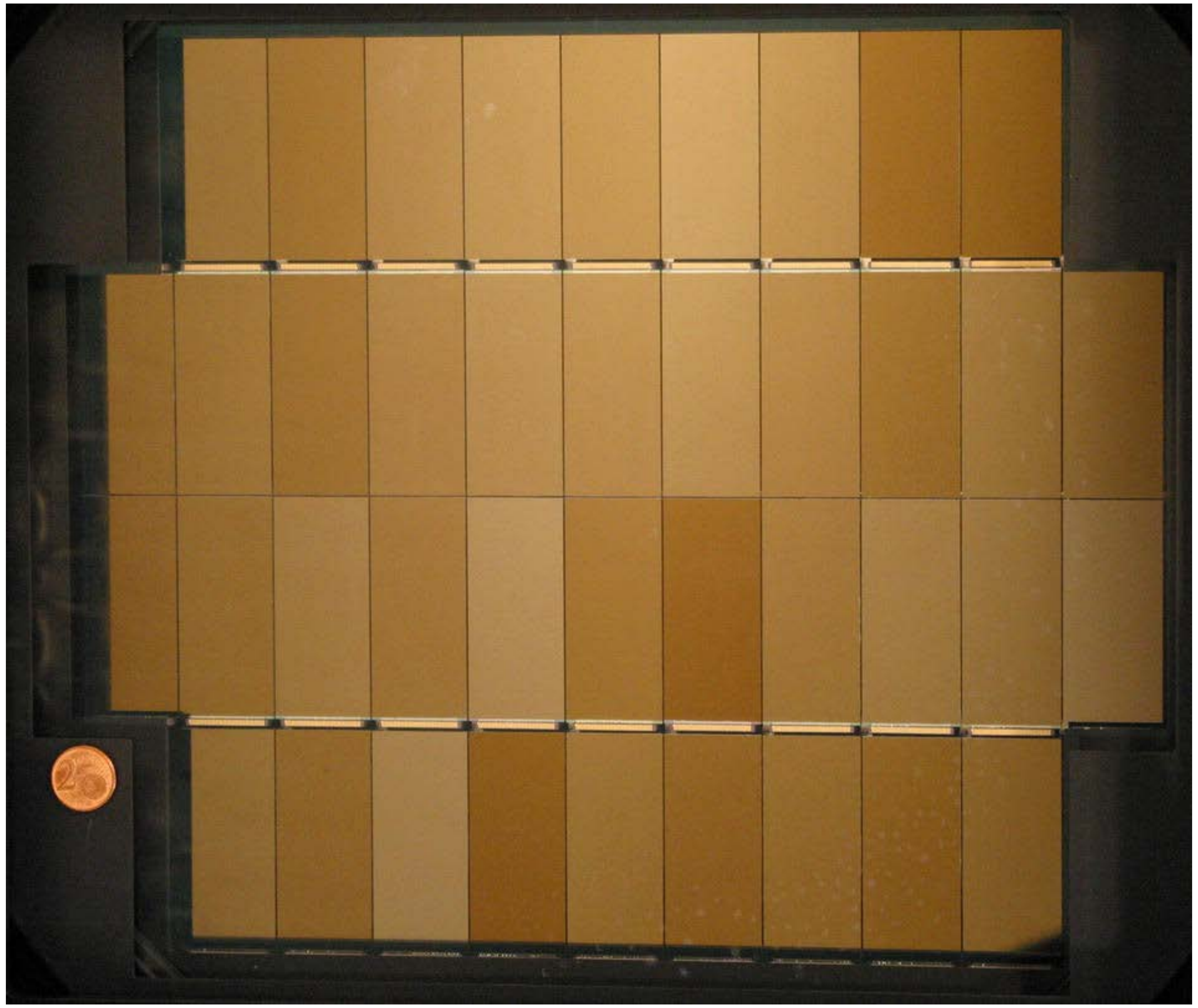
- For example at VLT/UT2:
  - Infra-red imager/spectrograph in Cassegrain focus (VISIR)
  - High-resolution optical spectrograph in one Nasmyth focus (UVES)
  - Multi-object medium/high-resolution spectrograph in other Nasmyth focus (FLAMES)



Detectors

- Once the light has gone through the telescope and instrument (imager, spectrograph), it has to be **recorded on a detector**
- Main detector type used today: **charge-coupled device (CCD)**, semi-conducting materials

CFHT MegaCam CCD (imaging)



Detectors

- Once the light has gone through the telescope and instrument (imager, spectrograph), it has to be **recorded on a detector**
- Main detector type used today: **charge-coupled device (CCD)**, semi-conducting materials
- The detector only knows about **photon count** and **X/Y position** on the detector, all physical interpretation needs to be done afterwards!
  - this is why we use **colour filters** for imaging
  - for spectra: need **wavelength calibration**

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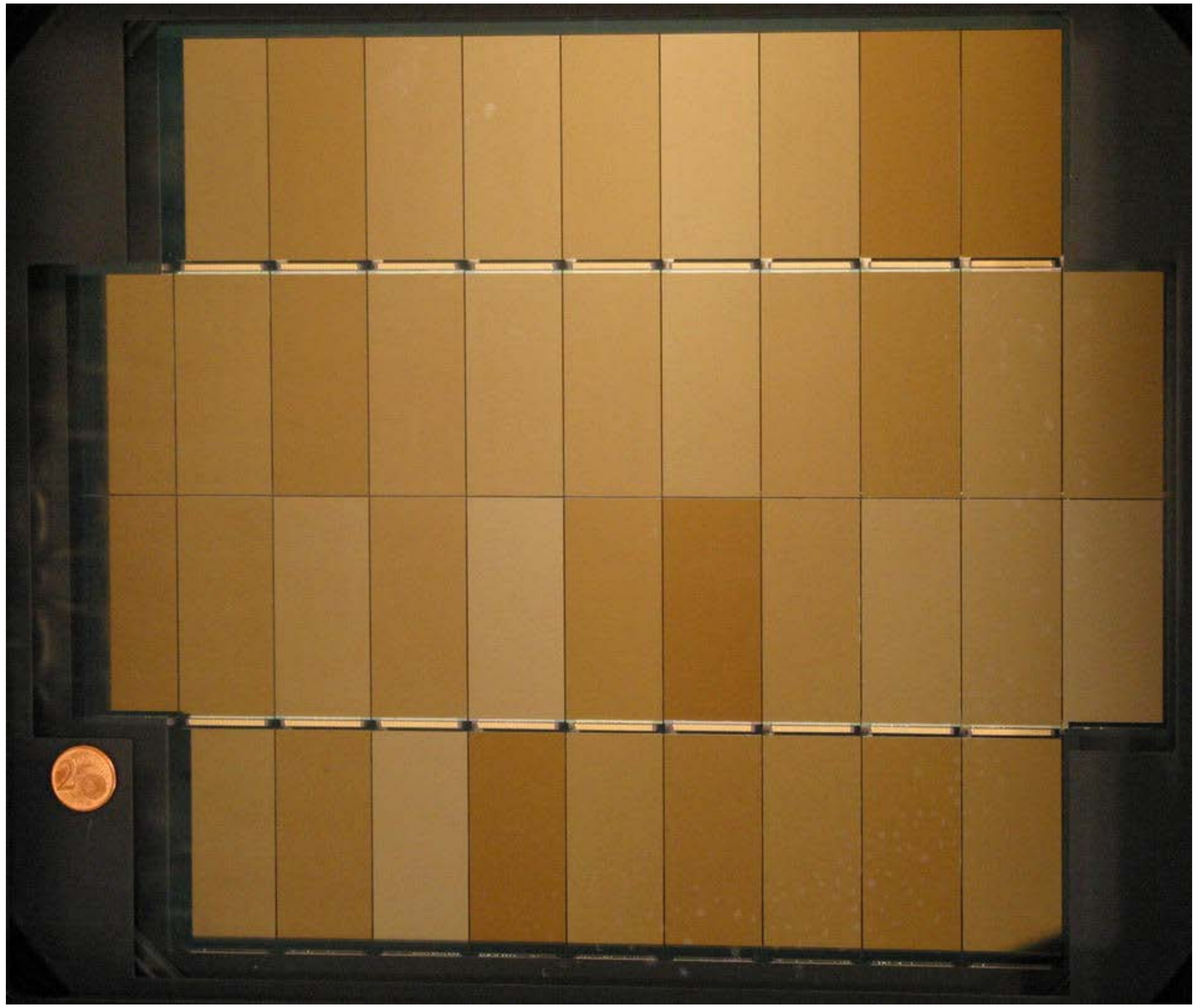

The typical observational research cycle

The typical observing cycle

- Idea/research question
- What kind of observations do I need? Which facility can provide these?

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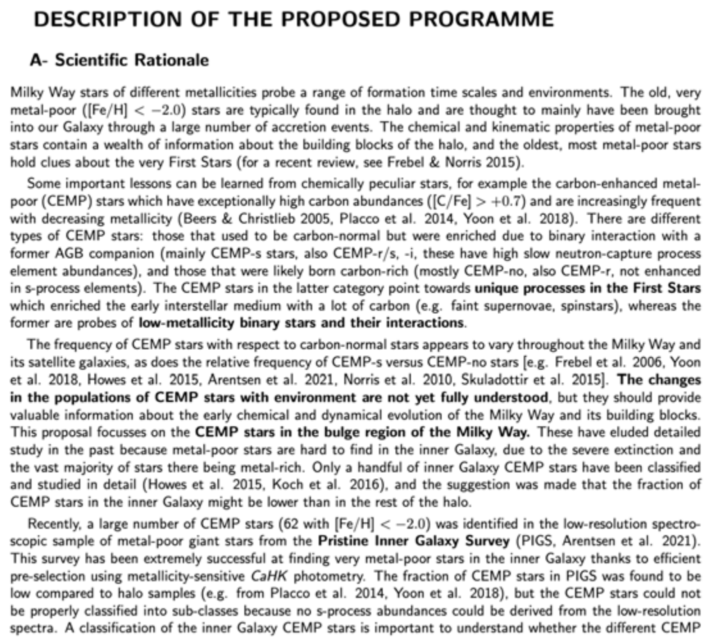
- Write a telescope proposal
    - Scientific justification
    - Technical justification



DESCRIPTION OF THE PROPOSED PROGRAMME

A- Scientific Rationale

Milky Way stars of different metallicities probe a range of formation time scales and environments. The old, very metal-poor ([Fe/H] < -2.0) stars are typically found in the halo and are thought to mainly have been brought into our Galaxy through a large number of accretion events. The chemical and kinematic properties of metal-poor stars contain a wealth of information about the building blocks of the halo, and the oldest, most metal-poor stars hold clues about the very First Stars (for a recent review, see Frebel & Norris 2015).

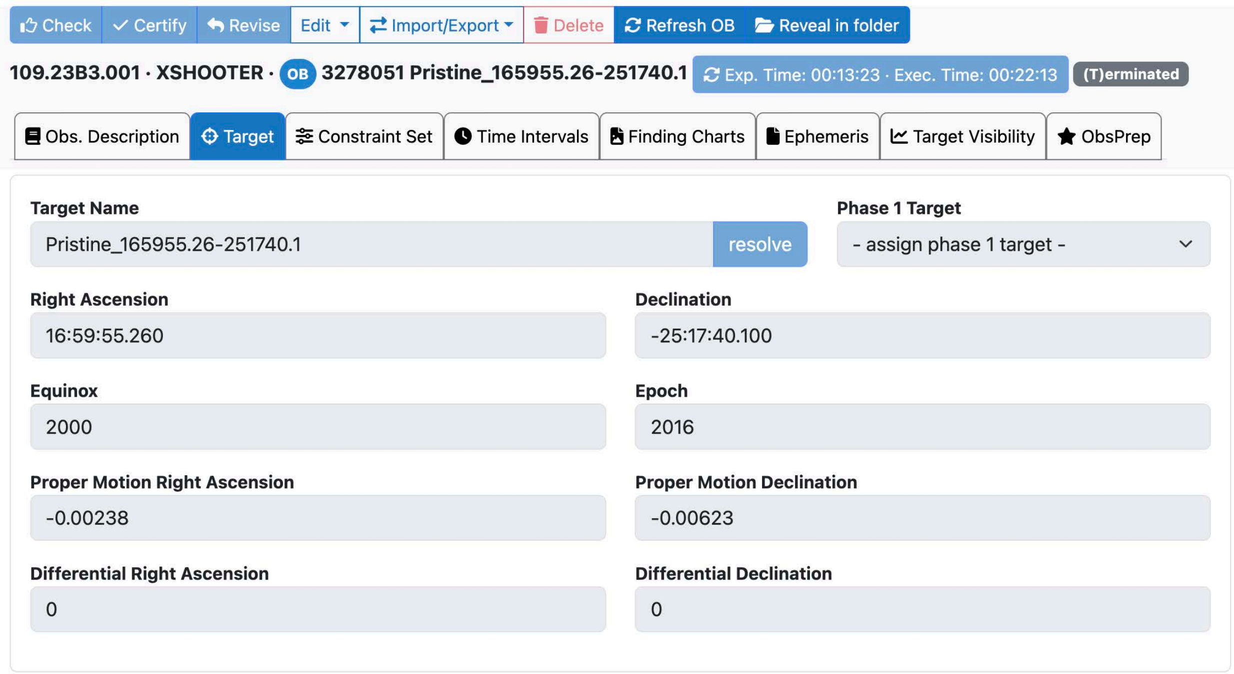
Some important lessons can be learned from chemically peculiar stars, for example the carbon-enhanced metal-poor (CEMP) stars which have exceptionally high carbon abundances ([C/Fe] $> +0.7$) and are increasingly frequent with decreasing metallicity (Beers & Christlieb 2005, Placco et al. 2014, Yoon et al. 2018). There are different types of CEMP stars: those that used to be carbon-normal but were enriched due to binary interaction with a former AGB companion (mainly CEMP-s stars, also CEMP-r/s, -i, these have high slow neutron-capture process element abundances), and those that were likely born carbon-rich (mostly CEMP-no, also CEMP-r, not enhanced in s-process elements). The CEMP stars in the latter category point towards **unique processes in the First Stars** which enriched the early interstellar medium with a lot of carbon (e.g. faint supernovae, spinstars), whereas the former are probes of **low-metallicity binary stars and their interactions**.

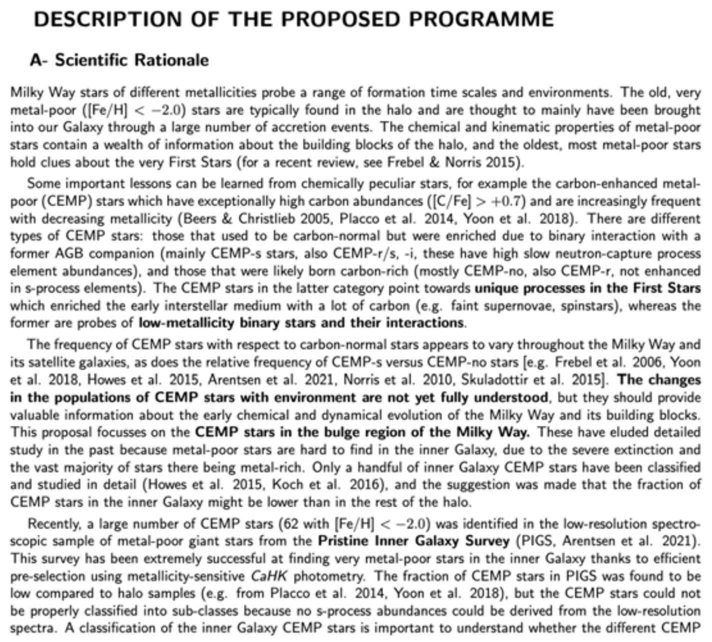
The frequency of CEMP stars with respect to carbon-normal stars appears to vary throughout the Milky Way and its satellite galaxies, as does the relative frequency of CEMP-s versus CEMP-no stars [e.g. Frebel et al. 2006, Yoon et al. 2018, Howes et al. 2015, Arentsen et al. 2021, Norris et al. 2010, Skuladottir et al. 2015]. **The changes in the populations of CEMP stars with environment are not yet fully understood**, but they should provide valuable information about the early chemical and dynamical evolution of the Milky Way and its building blocks. This proposal focusses on the **CEMP stars in the bulge region of the Milky Way.** These have eluded detailed study in the past because metal-poor stars are hard to find in the inner Galaxy, due to the severe extinction and the vast majority of stars there being metal-rich. Only a handful of inner Galaxy CEMP stars have been classified and studied in detail (Howes et al. 2015, Koch et al. 2016), and the suggestion was made that the fraction of CEMP stars in the inner Galaxy might be lower than in the rest of the halo.

Recently, a large number of CEMP stars (62 with [Fe/H] < -2.0) was identified in the low-resolution spectroscopic sample of metal-poor giant stars from the **Pristine Inner Galaxy Survey** (PIGS, Arentsen et al. 2021). This survey has been extremely successful at finding very metal-poor stars in the inner Galaxy thanks to efficient pre-selection using metallicity-sensitive *CaHK* photometry. The fraction of CEMP stars in PIGS was found to be low compared to halo samples (e.g. from Placco et al. 2014, Yoon et al. 2018), but the CEMP stars could not be properly classified into sub-classes because no s-process abundances could be derived from the low-resolution spectra. A classification of the inner Galaxy CEMP stars is important to understand whether the different CEMP

The typical observing cycle

- ➤ Idea/research question
- ➤ What kind of observations do I need? Which facility can provide these?
- ➤ Write a telescope proposal
  - ➤ Scientific justification
  - ➤ Technical justification
- ➤ If accepted:
  - ➤ prepare for observations
  - ➤ do the observations (your team or telescope operators)
  - ➤ get the raw data, next step: analyse





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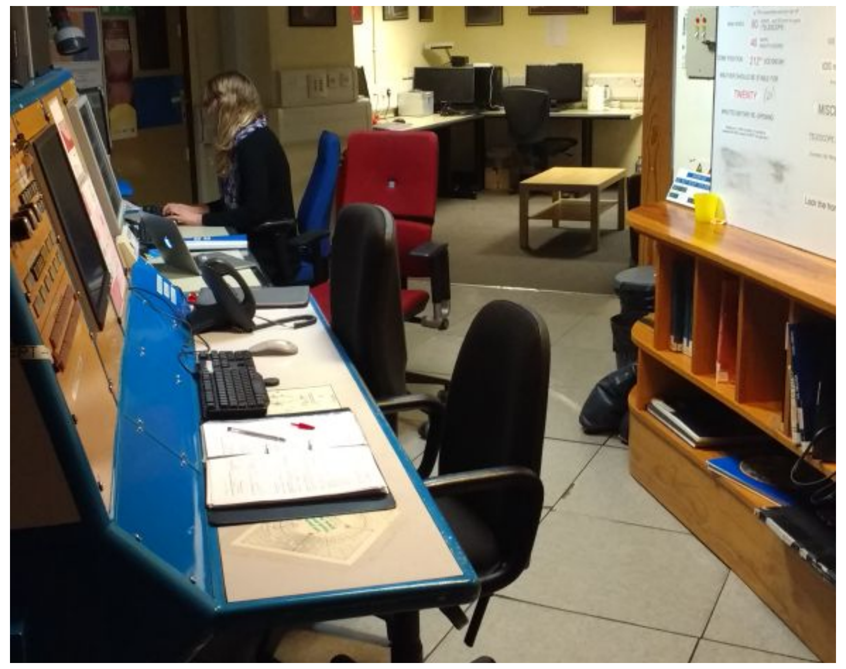

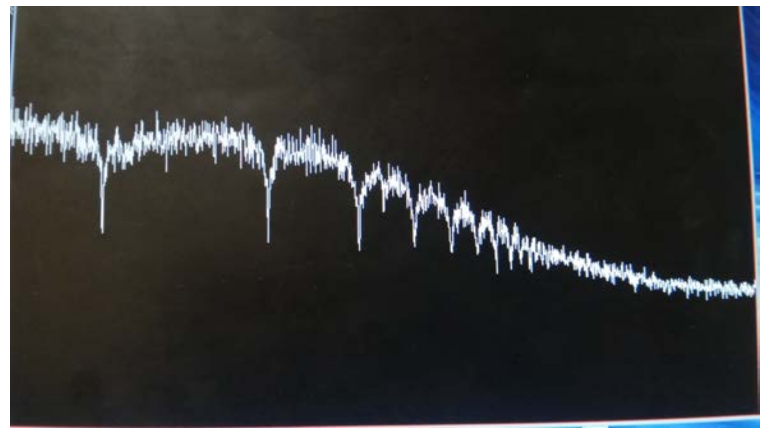

Getting started: scientific question/idea

e.g.:

- How old is this globular cluster?
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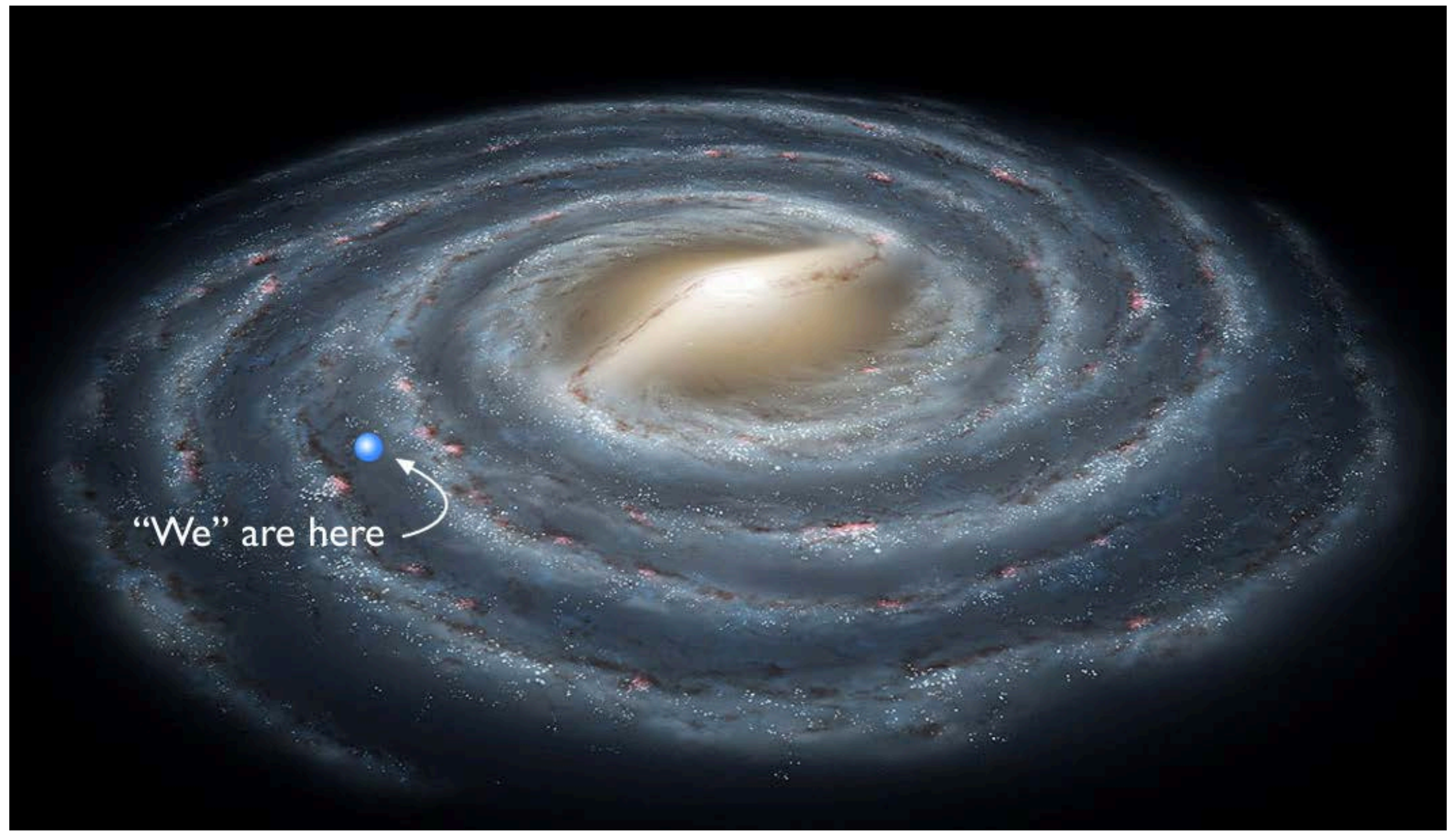
First Stars

early Galaxy formation



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- ➤ very metal-poor stars are very rare, especially in the inner Milky Way, so we need an efficient pre-selection method

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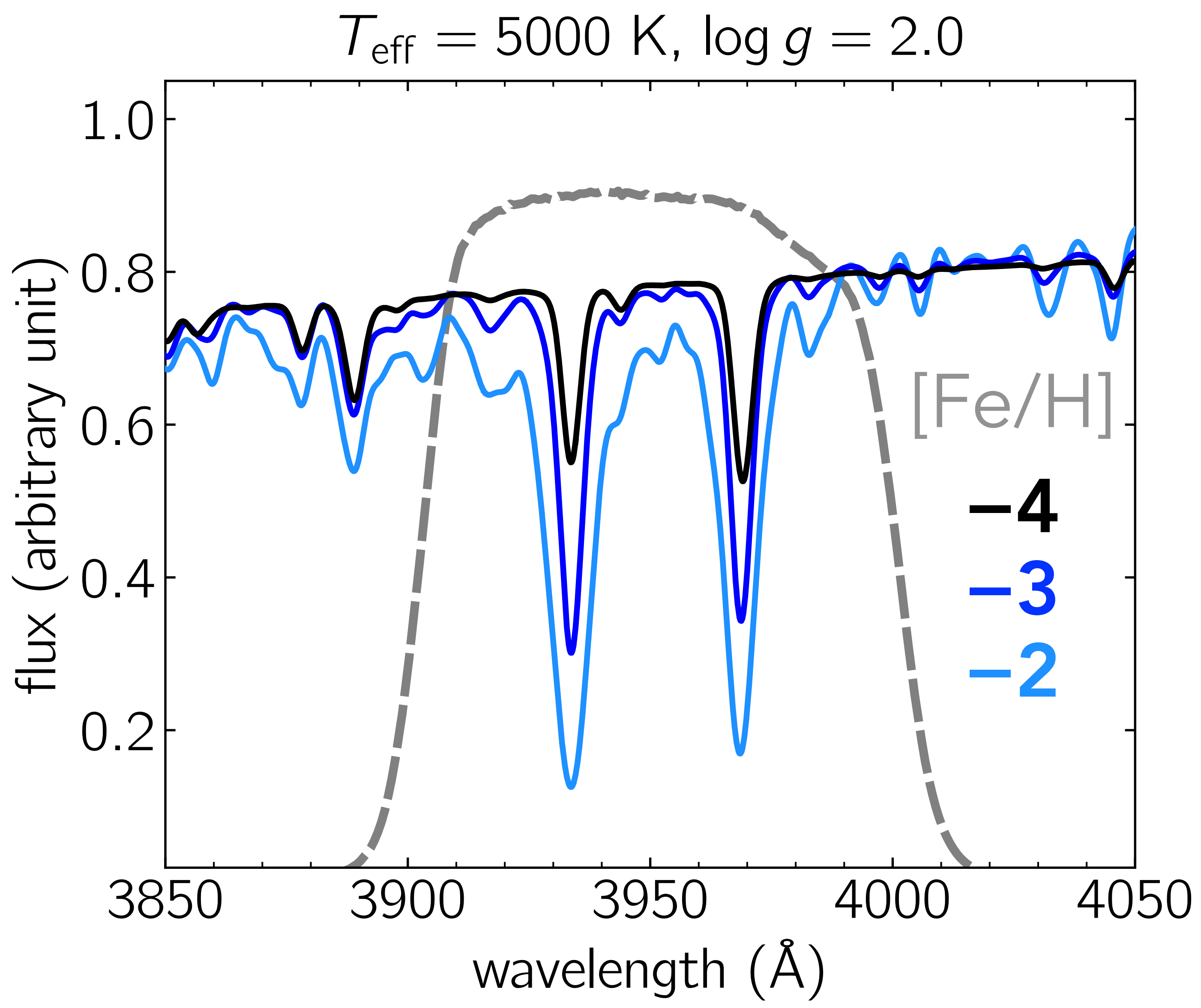
and this is how the "Pristine Inner Galaxy Survey" (PIGS) was born

How to find rare metal-poor stars?

- Photometry is much cheaper (faster/easier) than spectroscopy
- Pre-select metal-poor candidates using metallicity-sensitive narrow-band photometry

the calcium H&K lines



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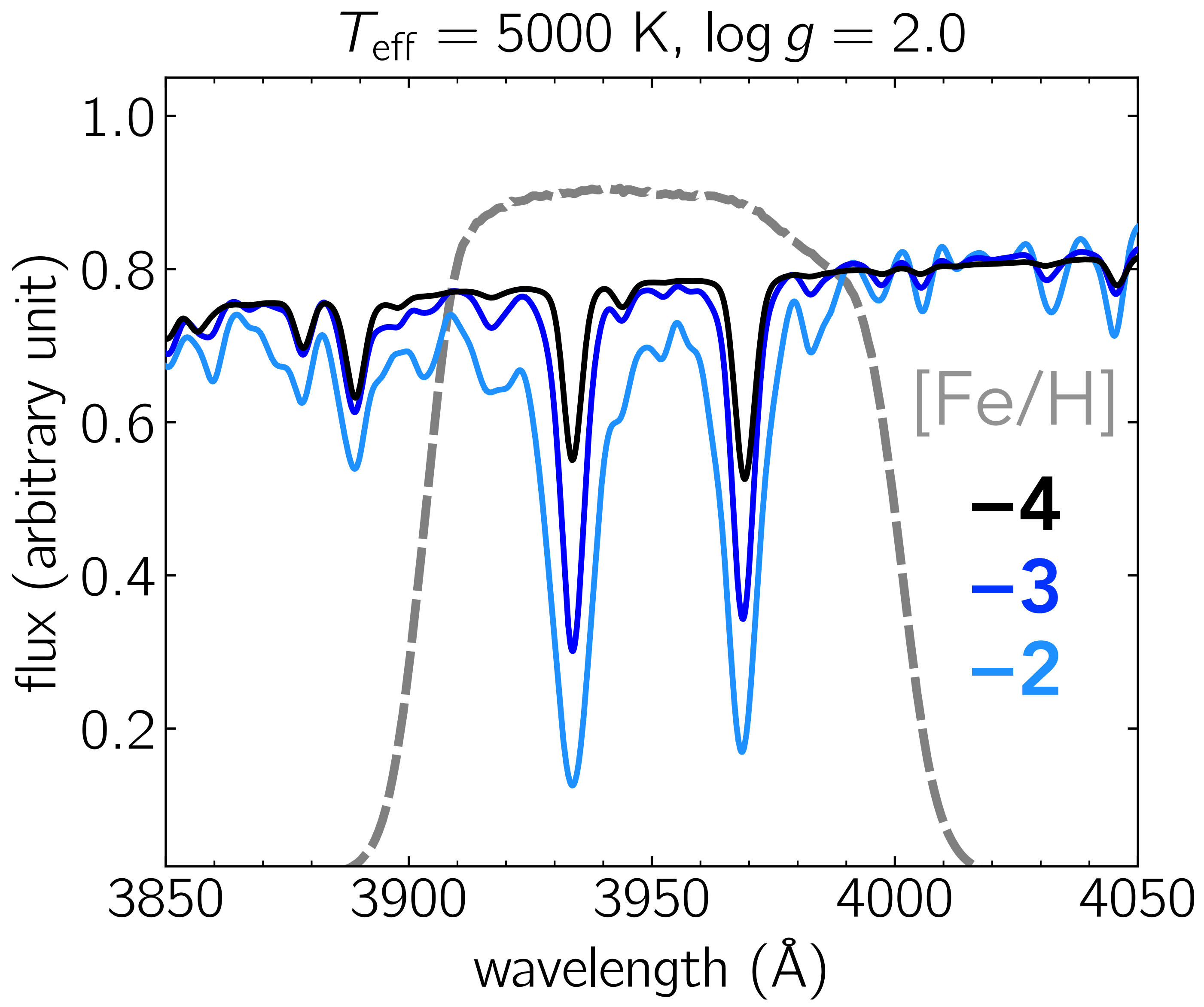

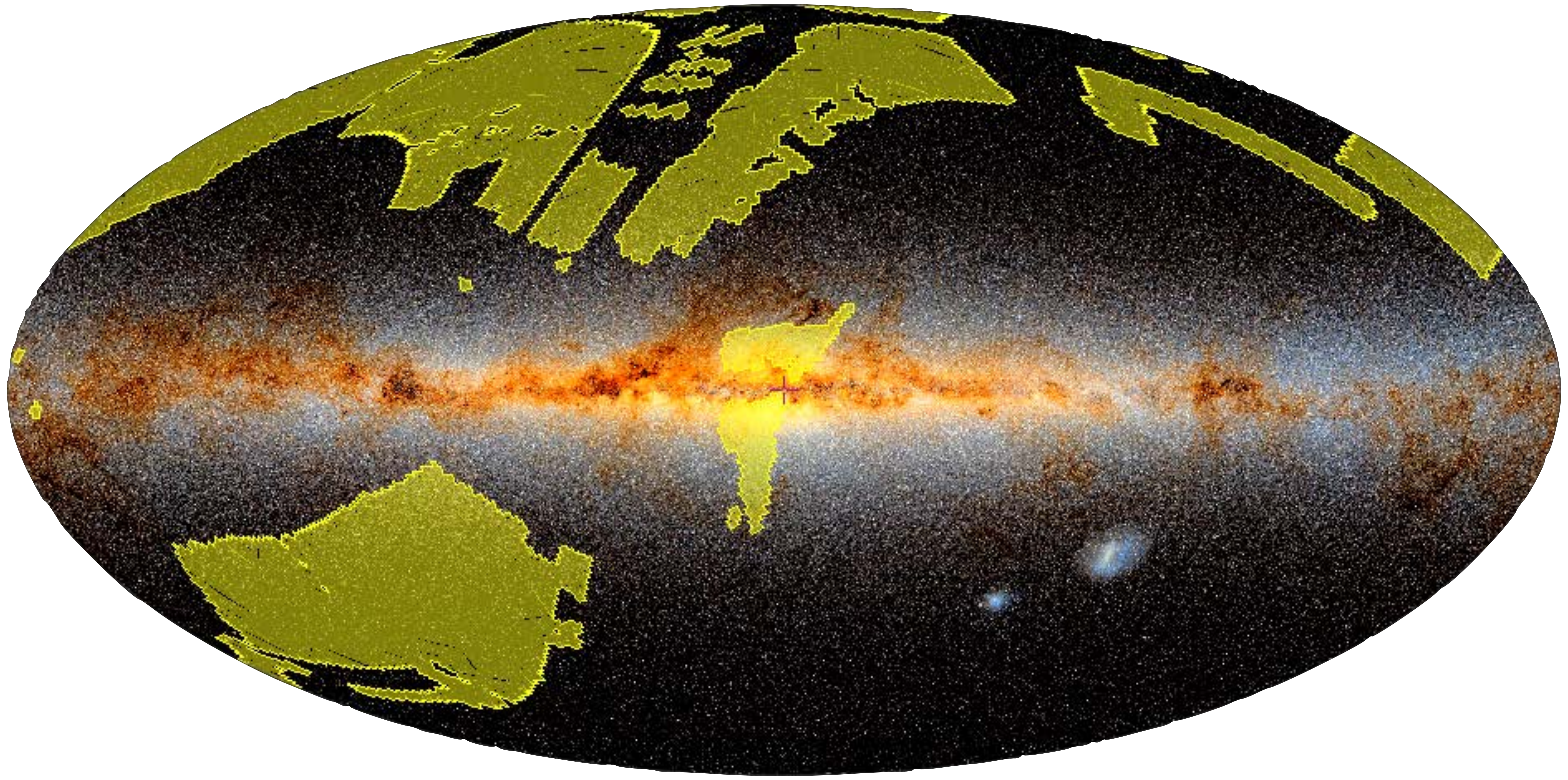

Pristine survey footprint, since 2017 and ongoing

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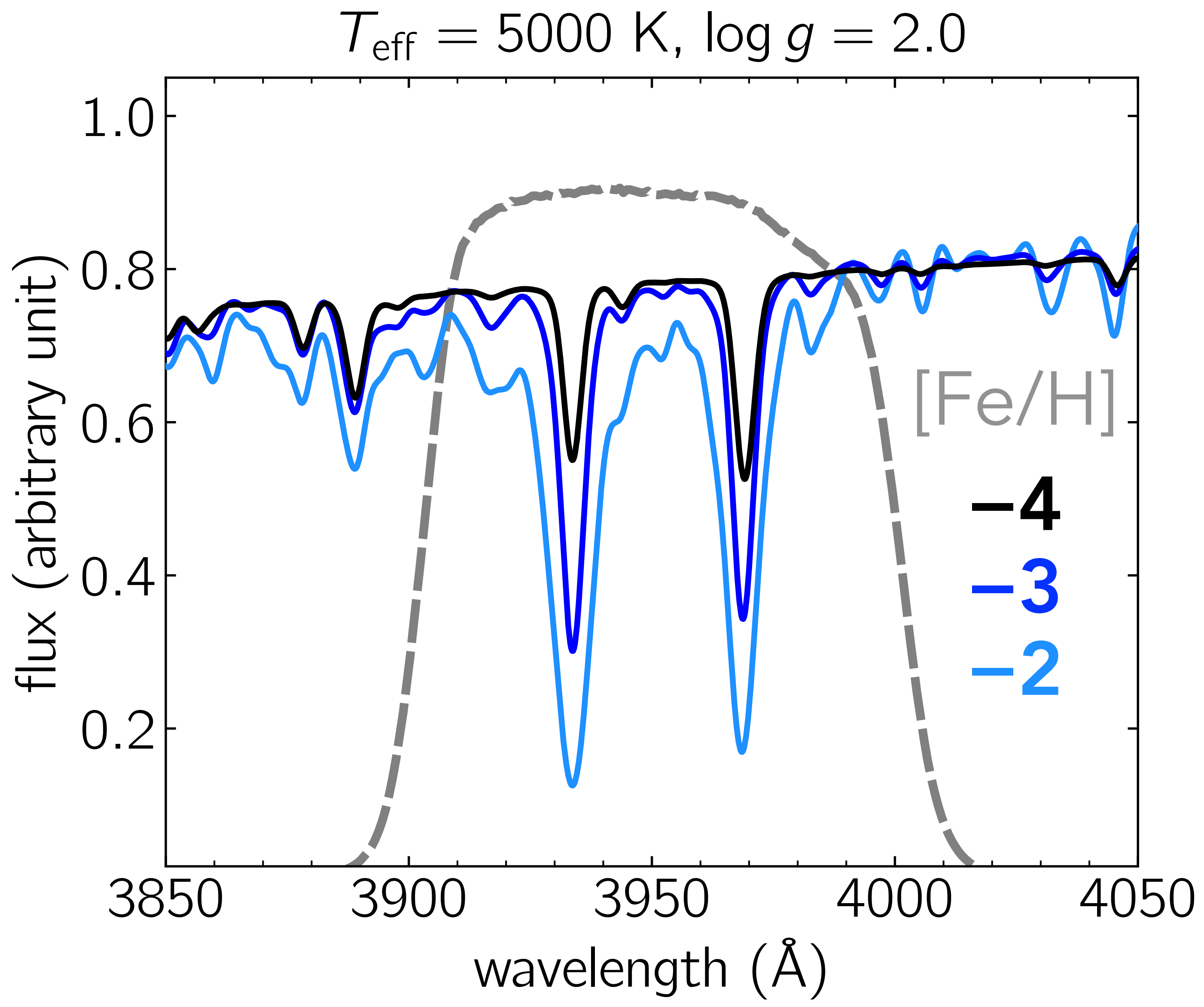

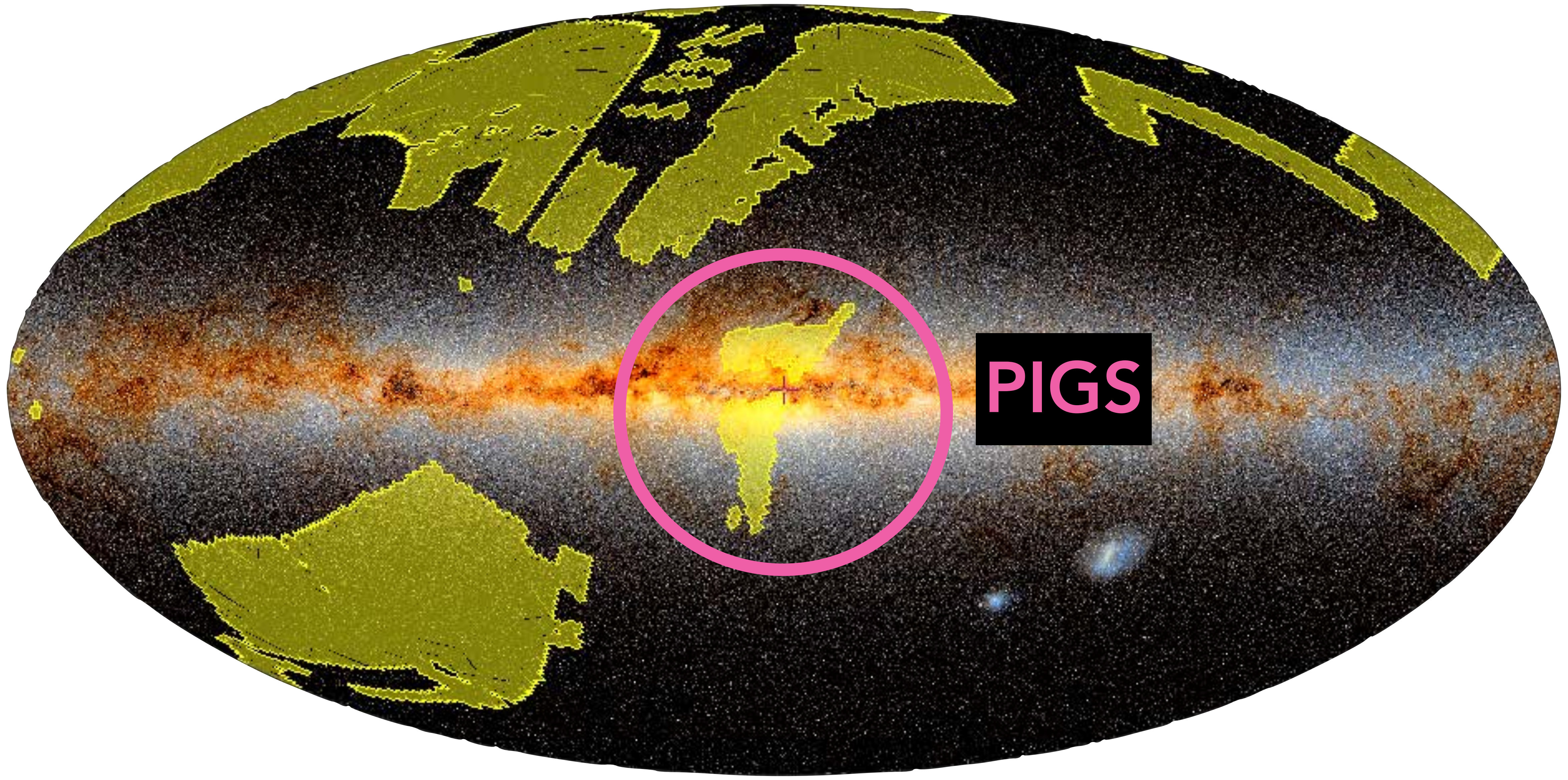

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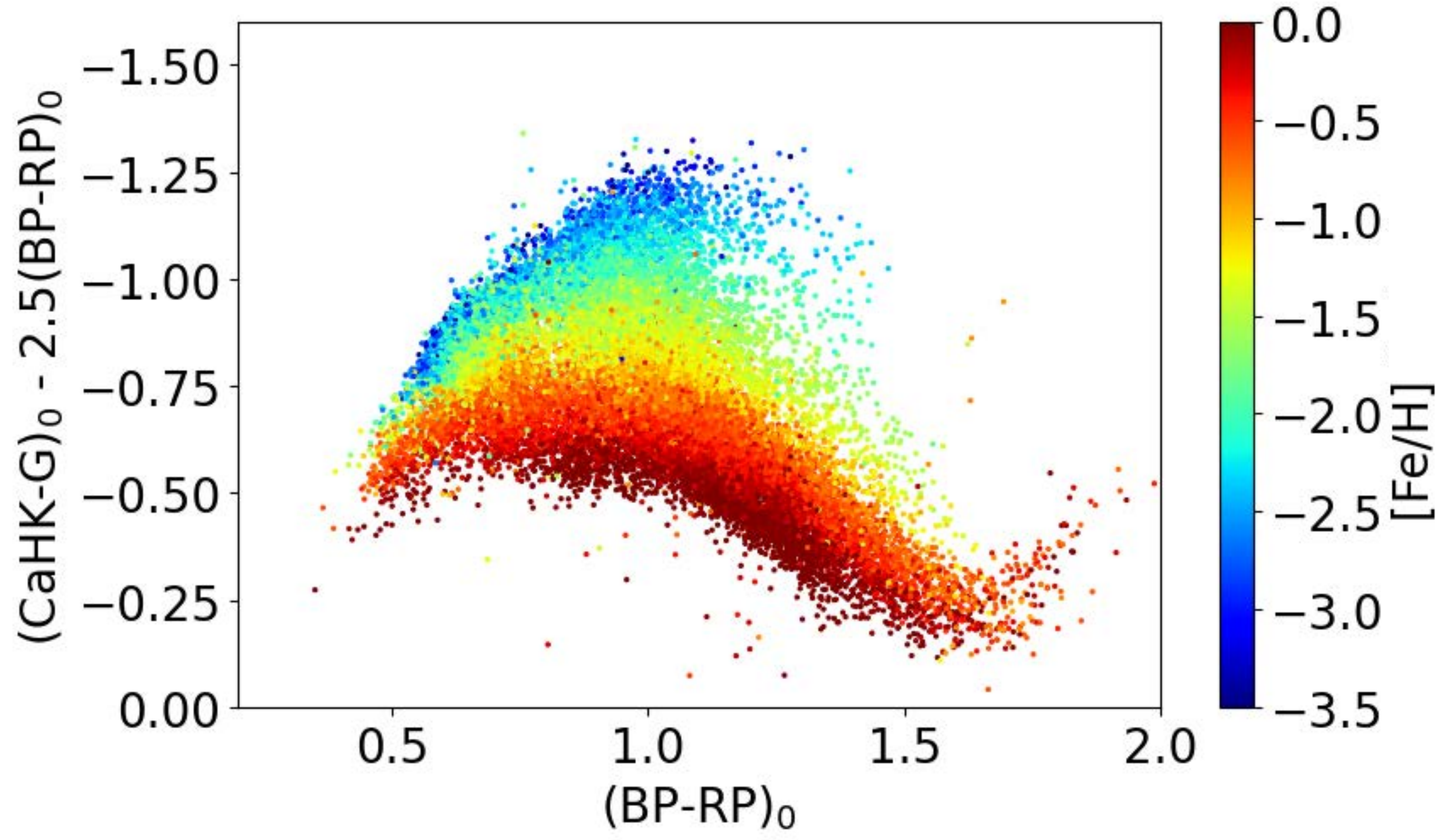

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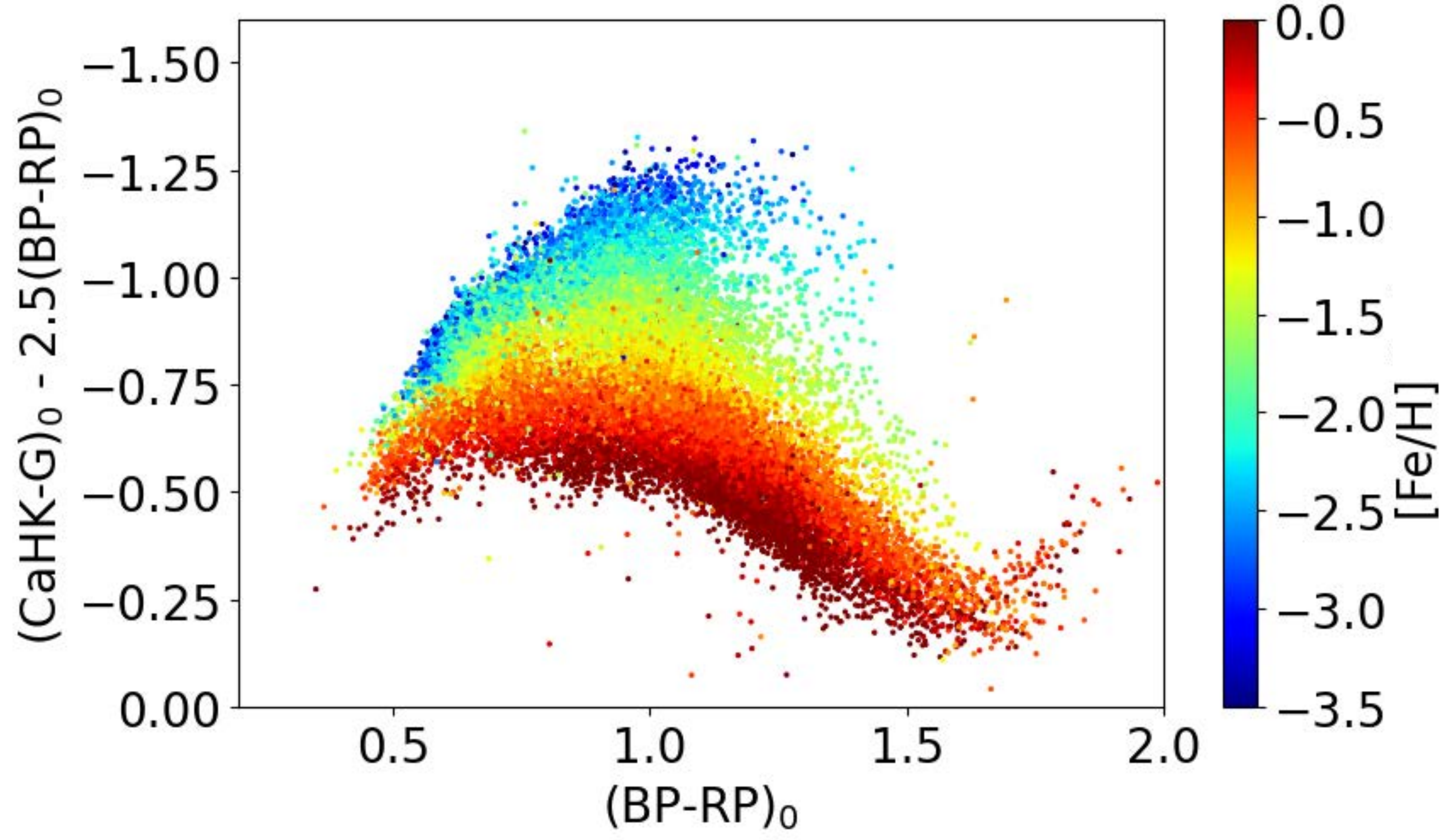
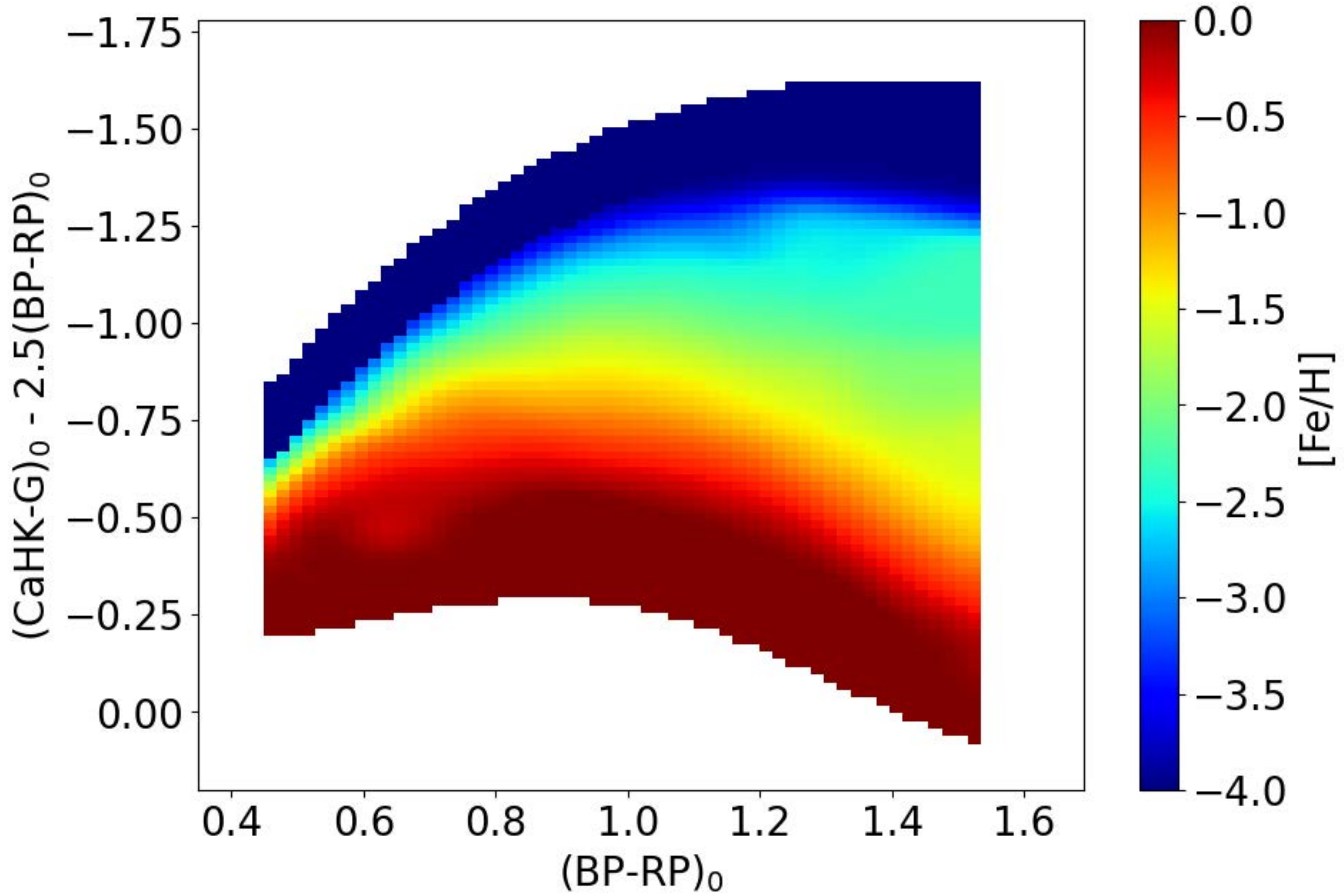


Model in the colour-colour space (binning & smoothing)



What kind of observations do I need?

- Step 1: photometric metallicities for target selection
- Step 2: spectroscopic metallicities, stellar parameters & radial velocities for analysis: low/medium-resolution spectra
- Step 3: high-resolution spectroscopic follow-up of most promising stars to get abundances

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What telescope can I use to obtain this data data?

- <u>Step 1</u>: need special *CaHK* filter, available at 4m Canada-France-Hawaii Telescope (CFHT)
  - Access through the largely Canadian/French *Pristine* collaboration
- <u>Step 2</u>: need to observe hundreds-thousands of stars efficiently: optical multi-object spectroscopy. Best instrument is the 2dF+AAOmega at the 4m AAT in Australia (~400 targets per pointing)
  - Access through special European time & collaborators in Australia

Write a telescope proposal

Important: when is the proposal submission deadline?!

(usually once per 6 months, ~March and September)

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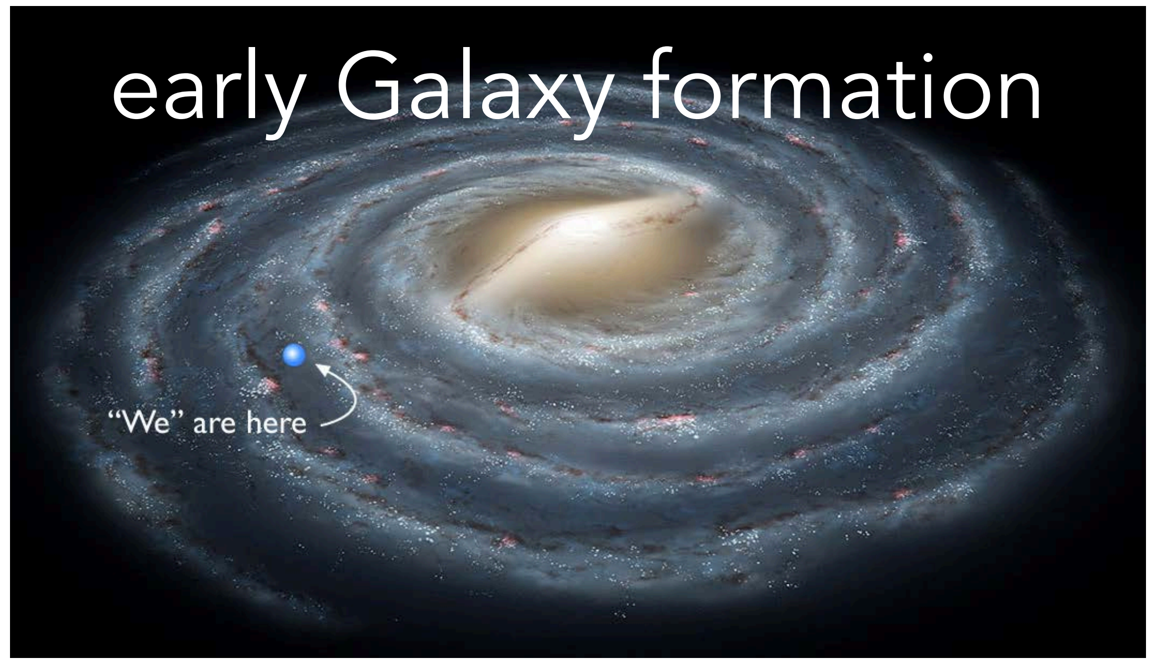
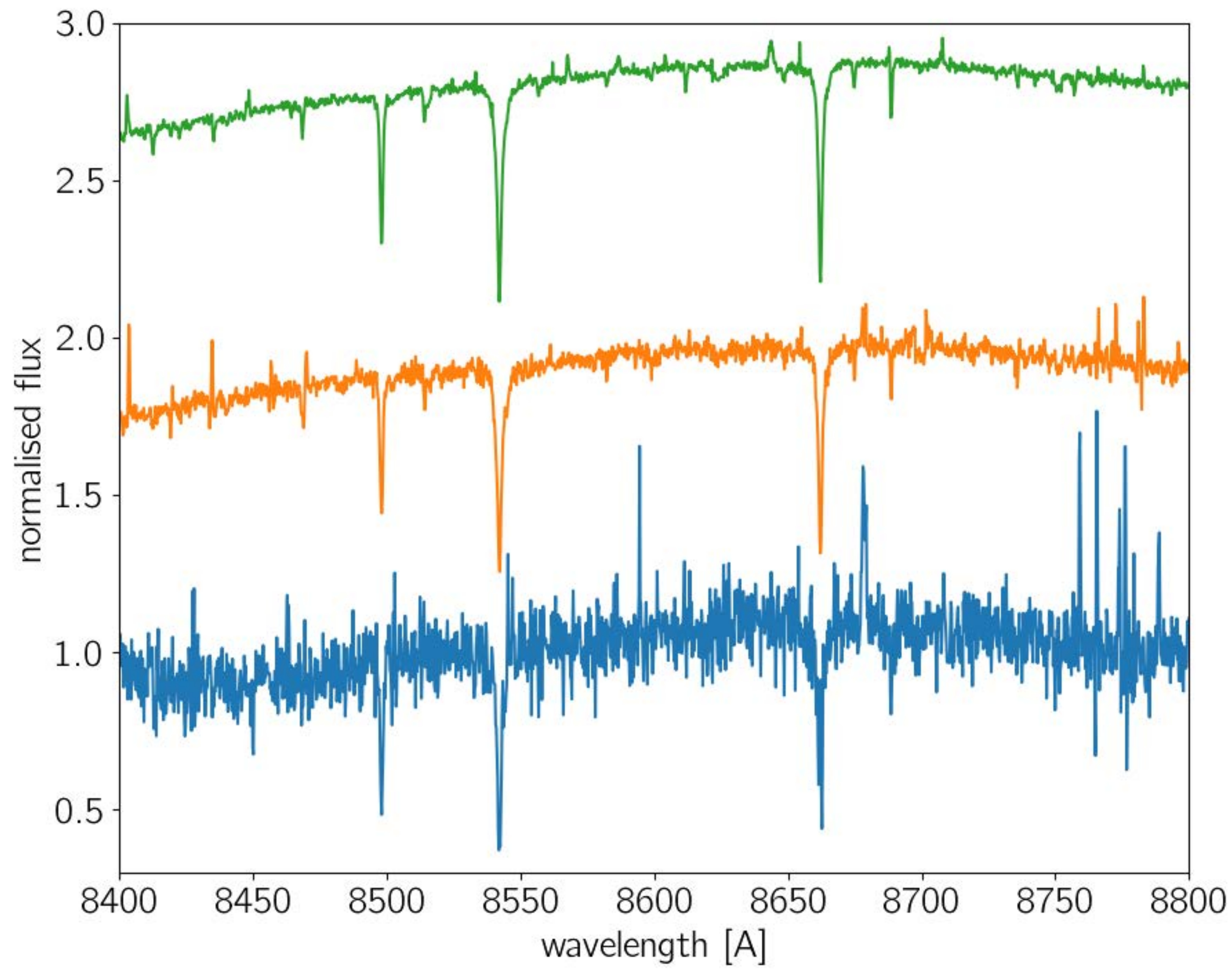
- Scientific justification (a few pages)
  - Why is this subject important or interesting? (for the broader astronomy community?)
  - What is the exact question the proposal aims to address?
  - Exactly how will the proposed observations address this question?



Write a telescope proposal

- Technical justification (typically ~a page)
  - Why the chosen instrument/setup/resolution? Need specific calibrations?
  - Sample size, S/N, integration times, conditions (use exposure time calculator: ETC)
  - Why exactly this amount of observations, not more/less?
  - How will the data be analysed?

S/N of 120, 50 and 13 (top to bottom)



PIGS pilot program

Telescope proposals:

- **April 2017 (DDT special proposal), CFHT:**
  - test our strategy
  - 3 hours of observing time
  - cover ~40 deg^2 to a depth of G~19, overlap with known spectroscopy

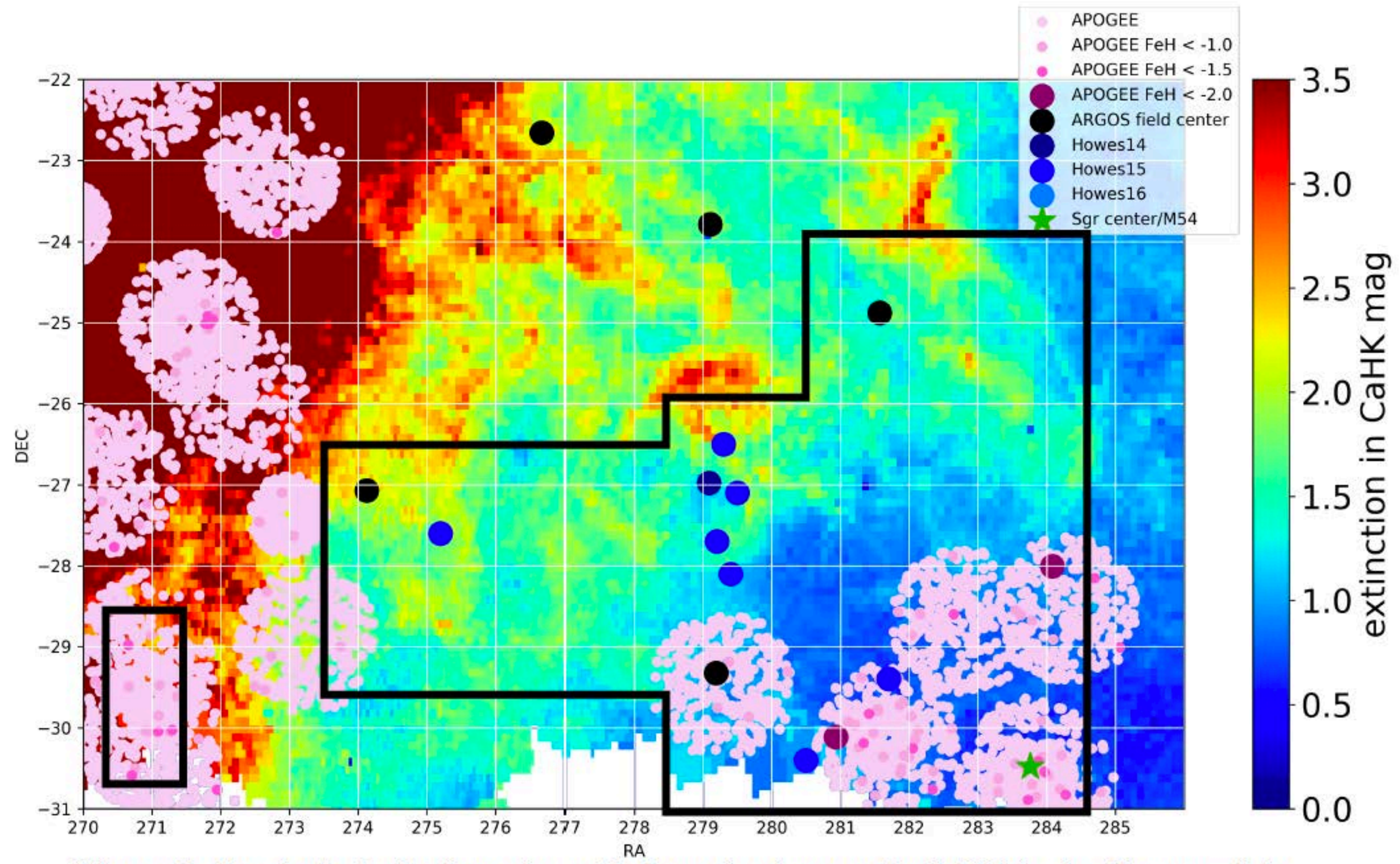


Figure 3: Our desired pilot footprint, with the extinction map in CaHK (at the distance of the bulge) in the background. It covers regions with different extinction and crowding.

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- **April 2017 (DDT special proposal), CFHT:**
  - test our strategy
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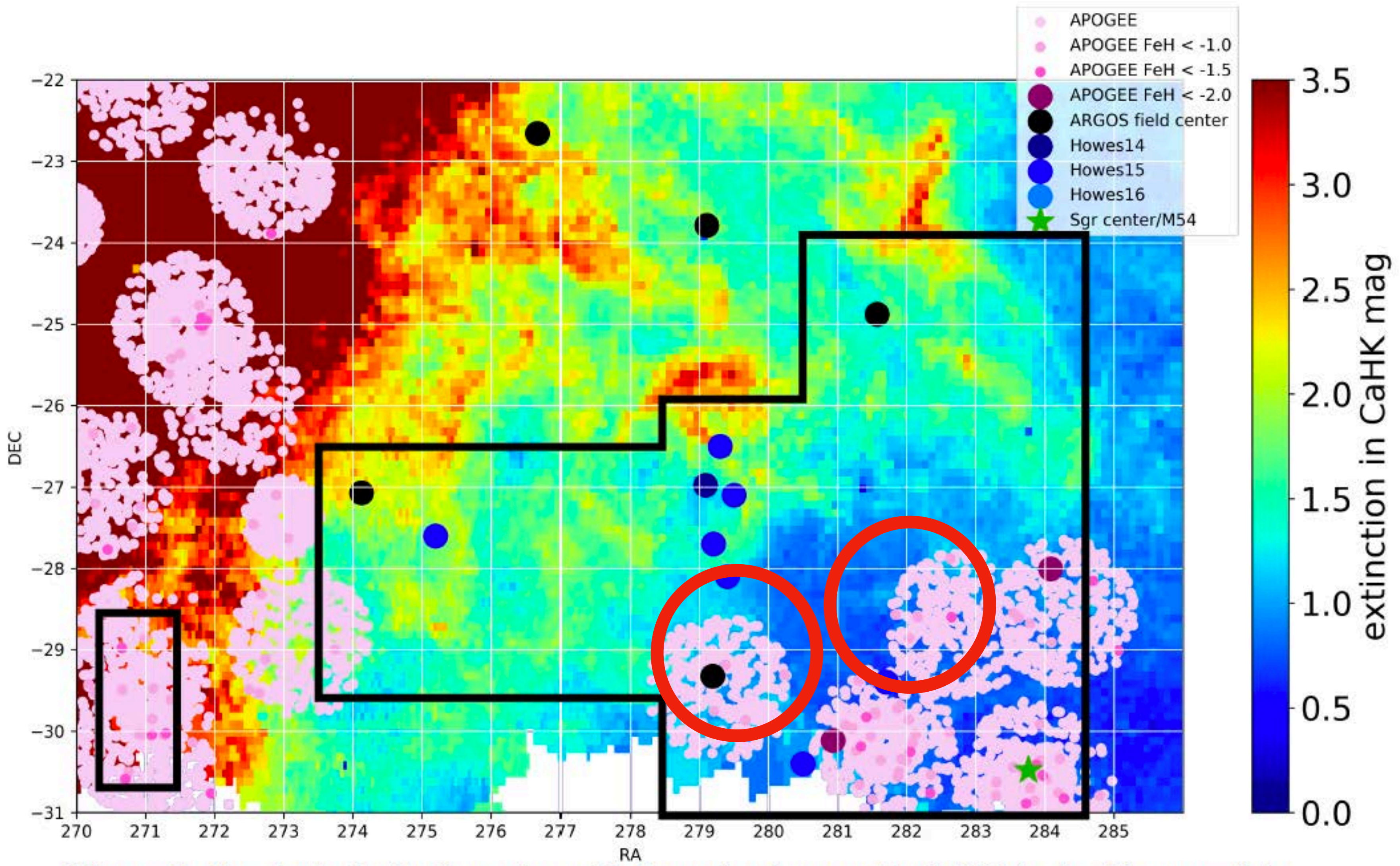
- **August 2017 (DDT special proposal), AAT:**
  - test our strategy
  - 2x2 hours of observing time
  - observe ~400 candidate metal-poor stars over two AAT fields, with $14 < G < 17$, S/N ~ 20



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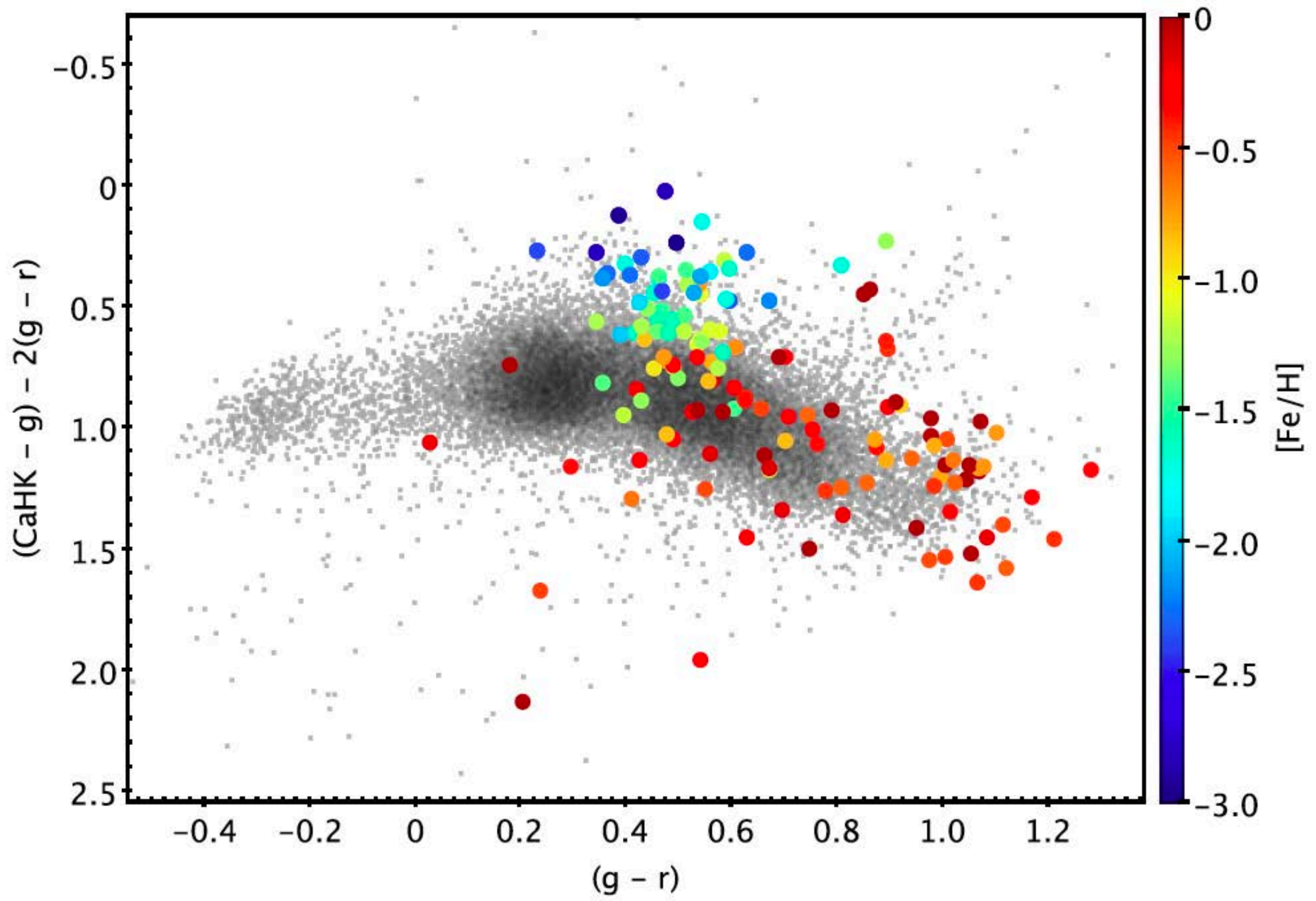

After submitting the proposal

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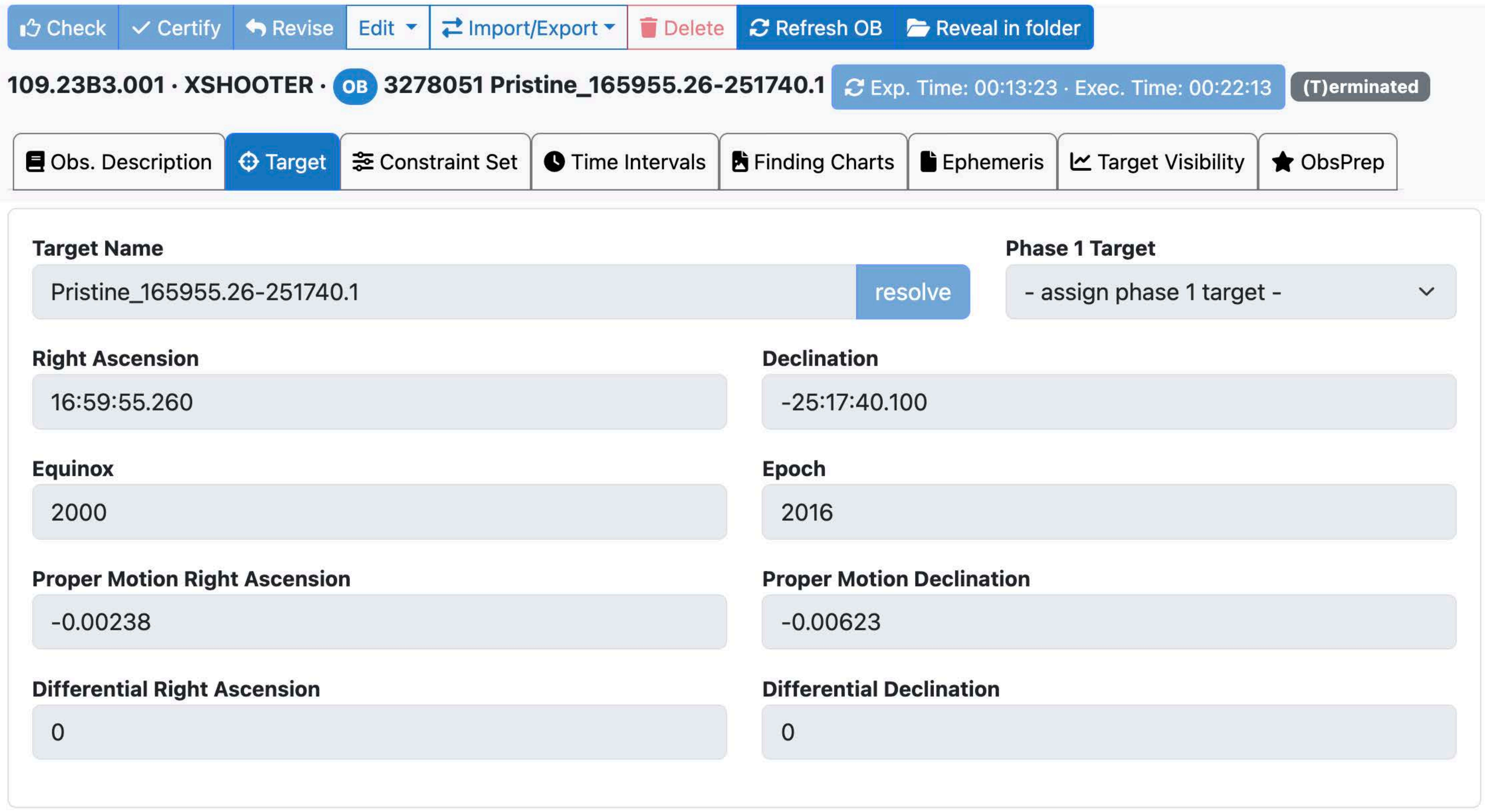
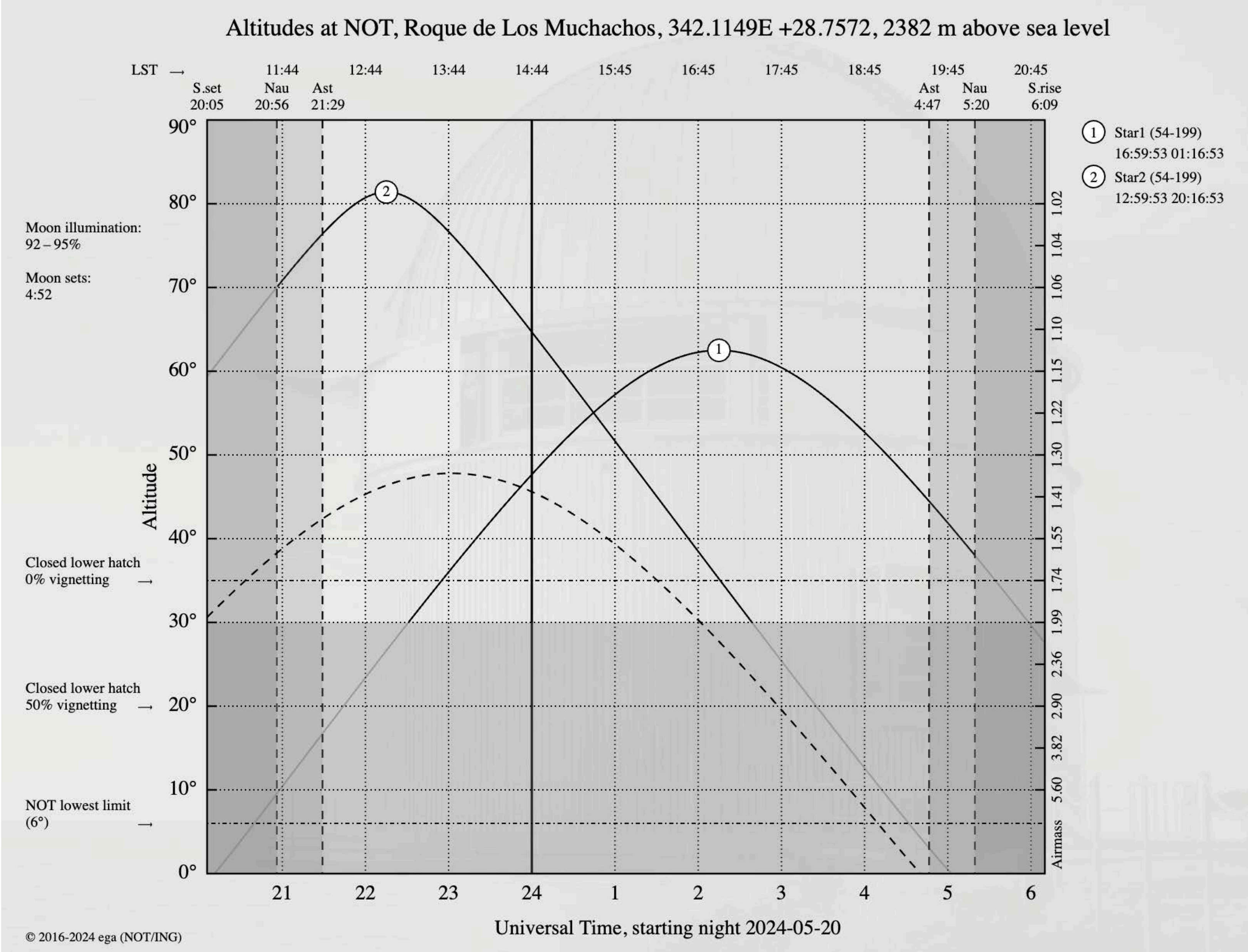
- If proposal is accepted, prepare the observations in detail ("Phase 2") for execution
  - *e.g. coordinates, brightness, exposure time, and when is it observable?*





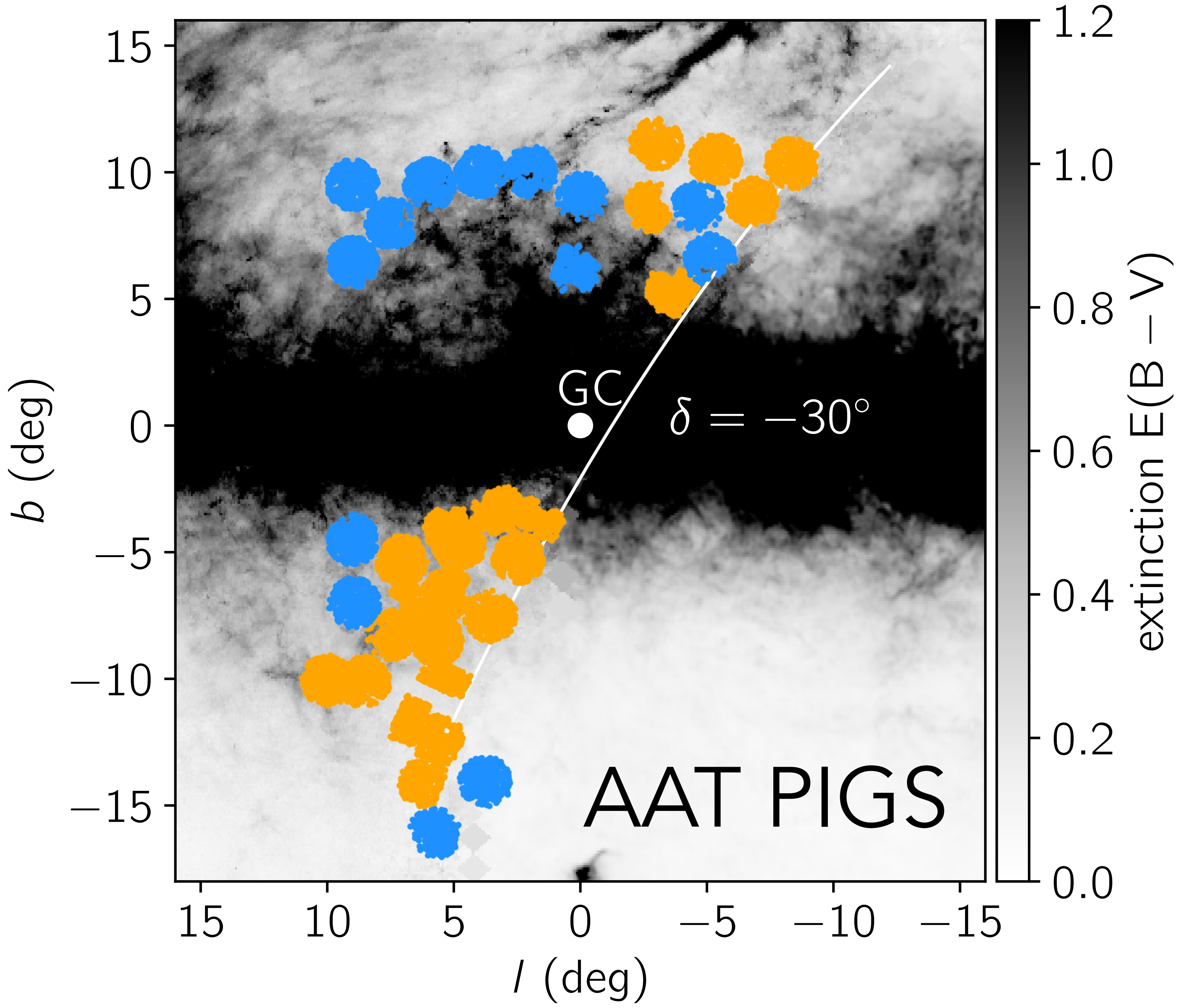
Further PIGS proposals

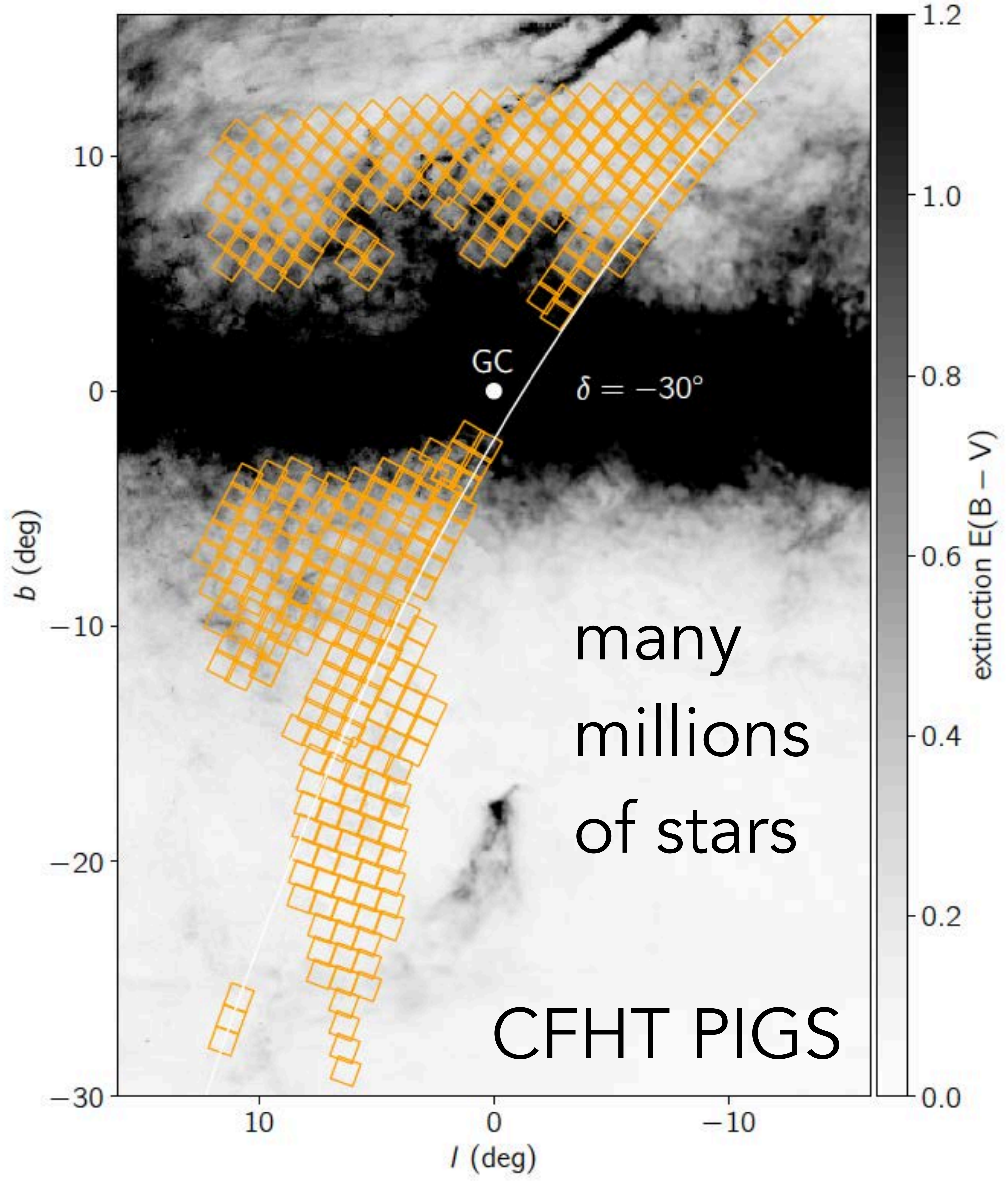
- 2 CFHT proposals in 2017/2018 (33 hours total) + piggyback on main *Pristine* survey
- 4 AAT proposals from 2017-2019 (13 nights total)

First 2 years

Final year

13 000 stars





Further PIGS proposals

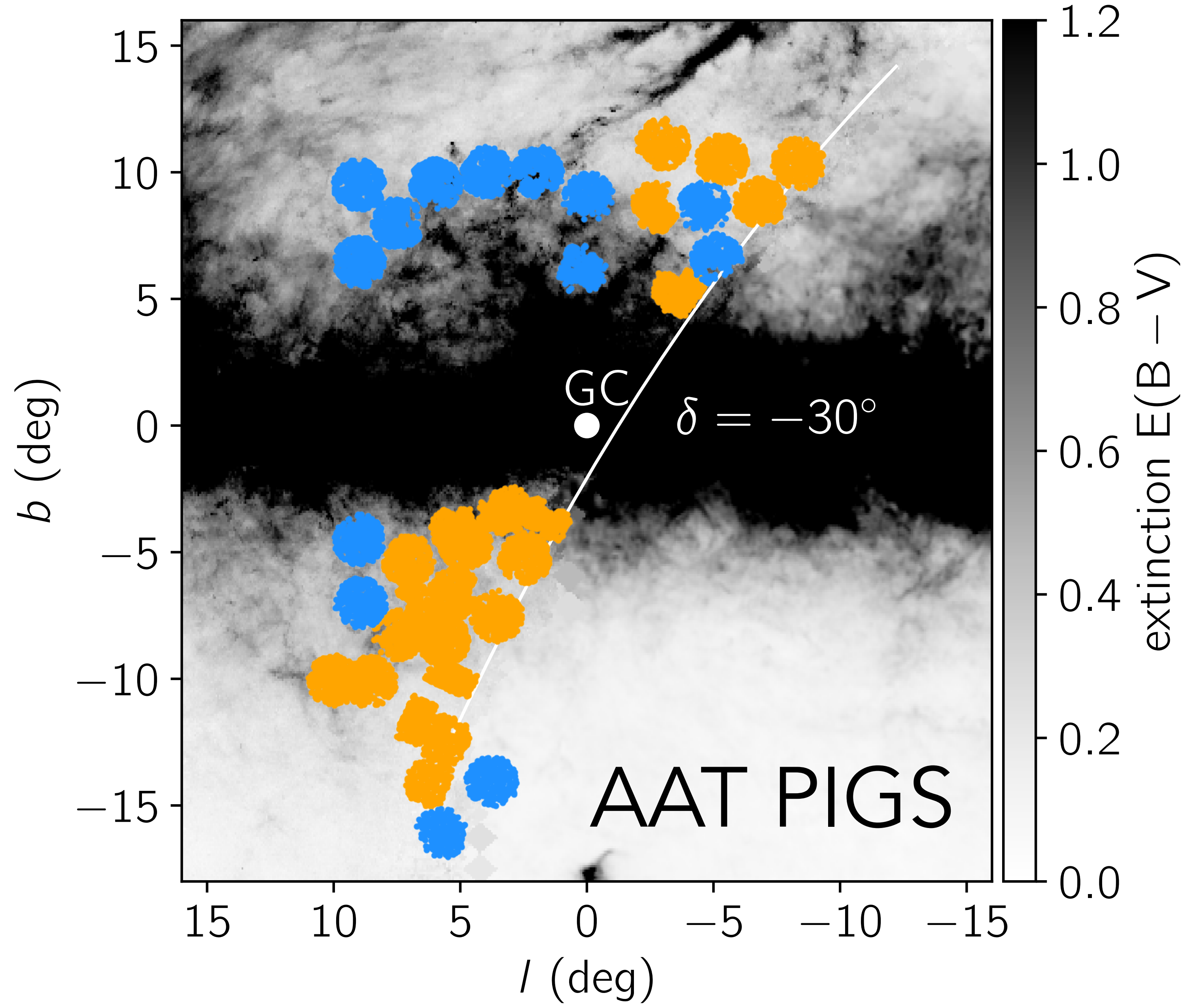
- 2 CFHT proposals in 2017/2018 (33 hours total) + piggyback on main *Pristine* survey
- 4 AAT proposals from 2017-2019 (13 nights total)

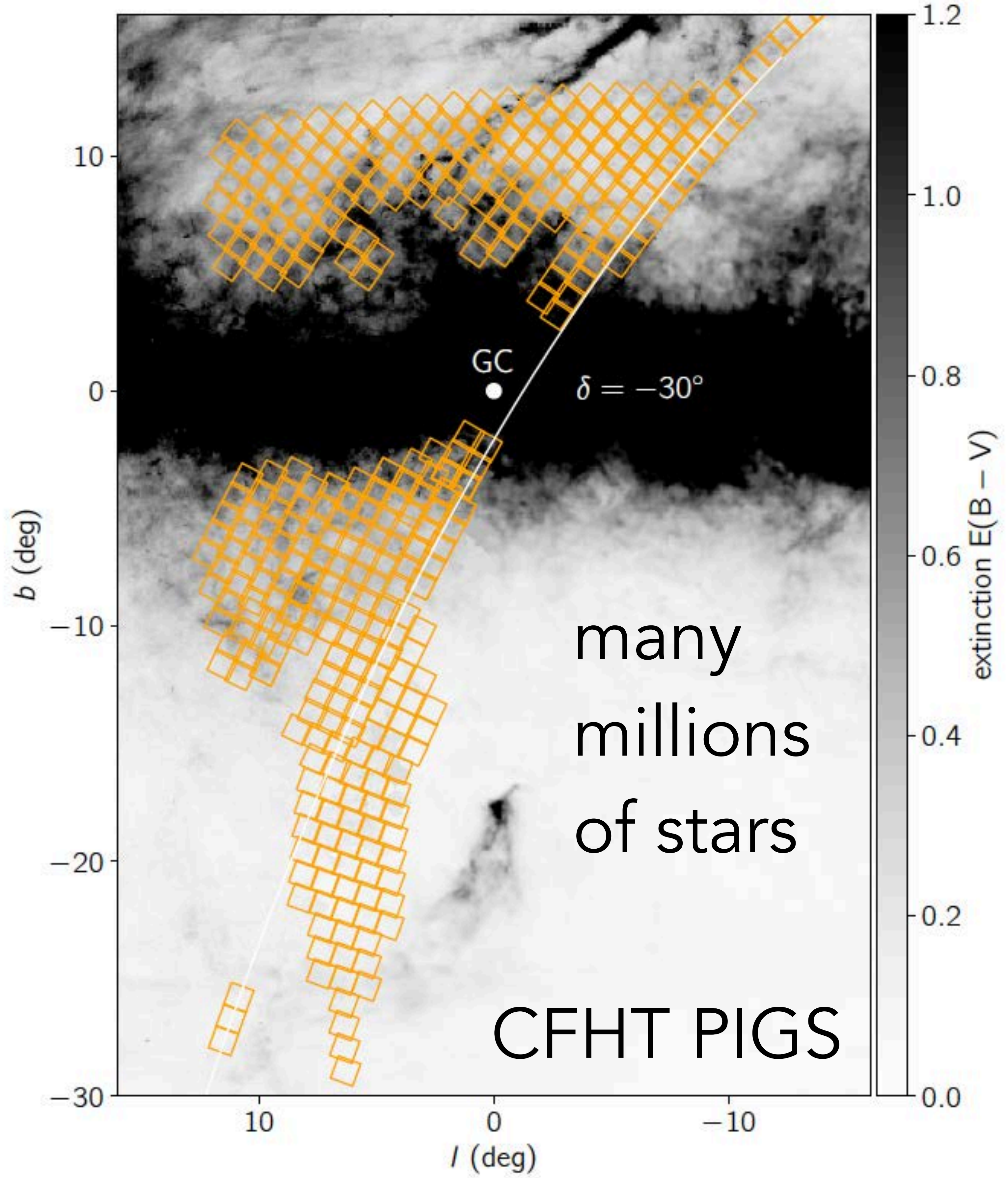
+ high-resolution follow-up with the VLT and Gemini telescopes in 2018, 2020 & 2022 (70 hours), **~50 stars**

First 2 years

Final year

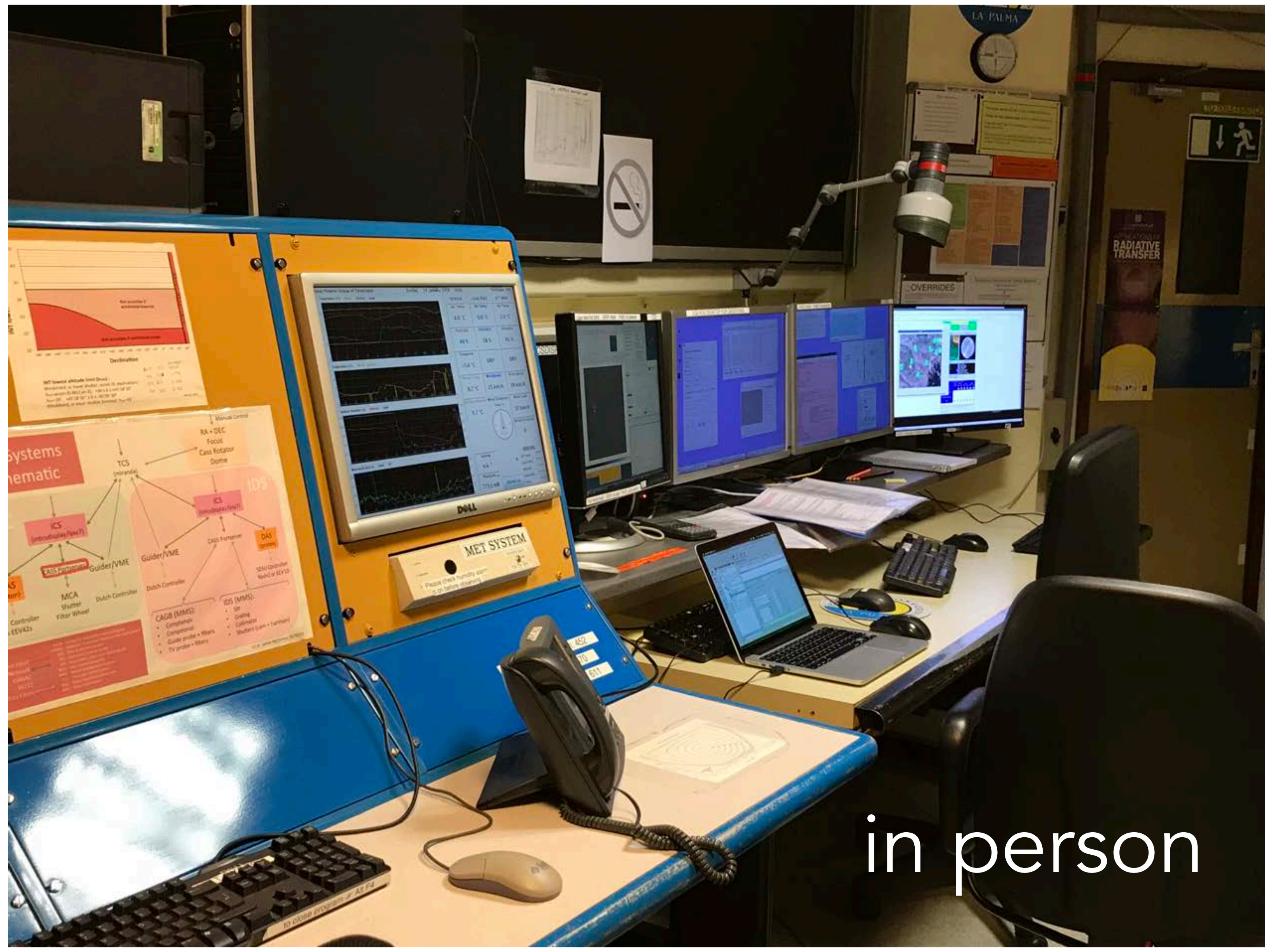
13 000 stars



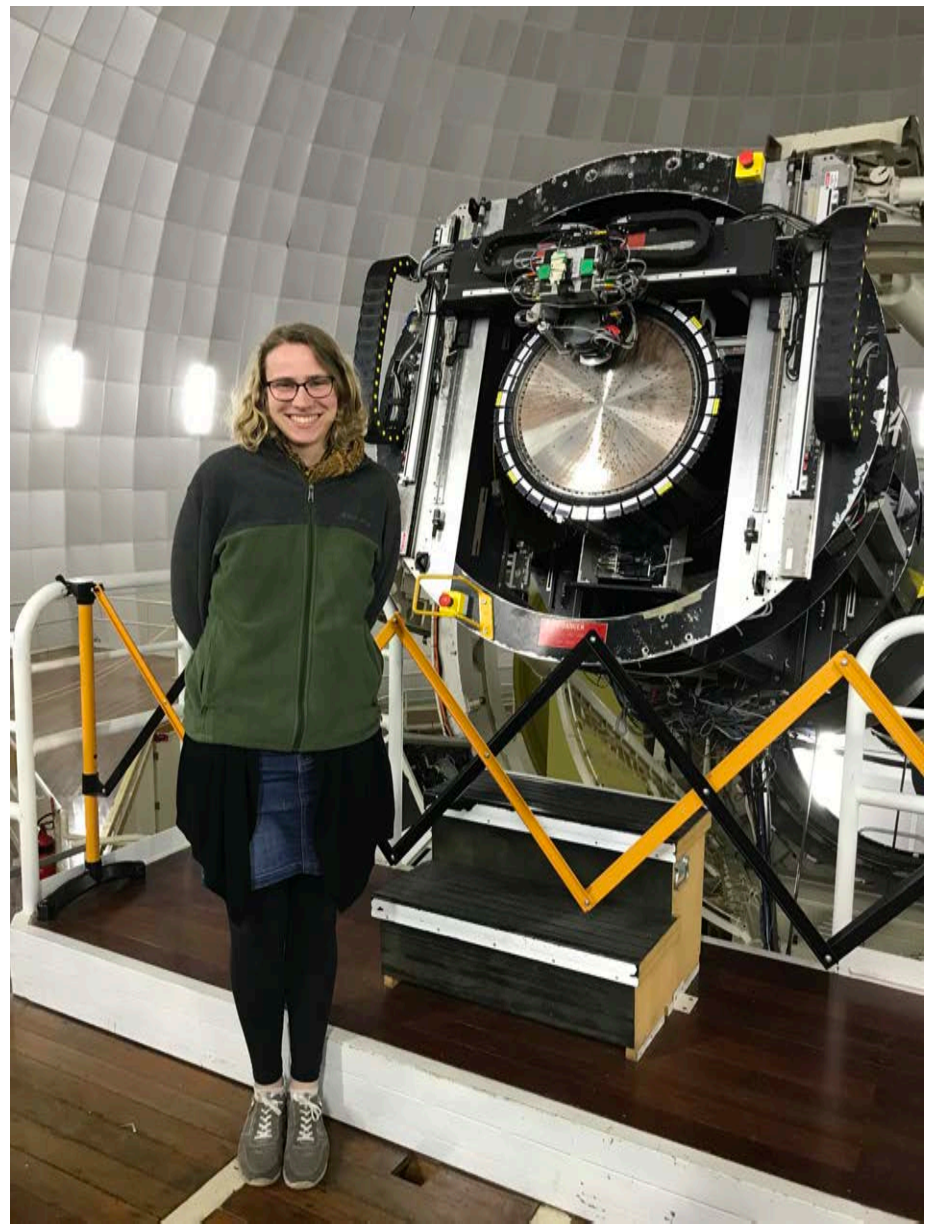


Observing

AAT



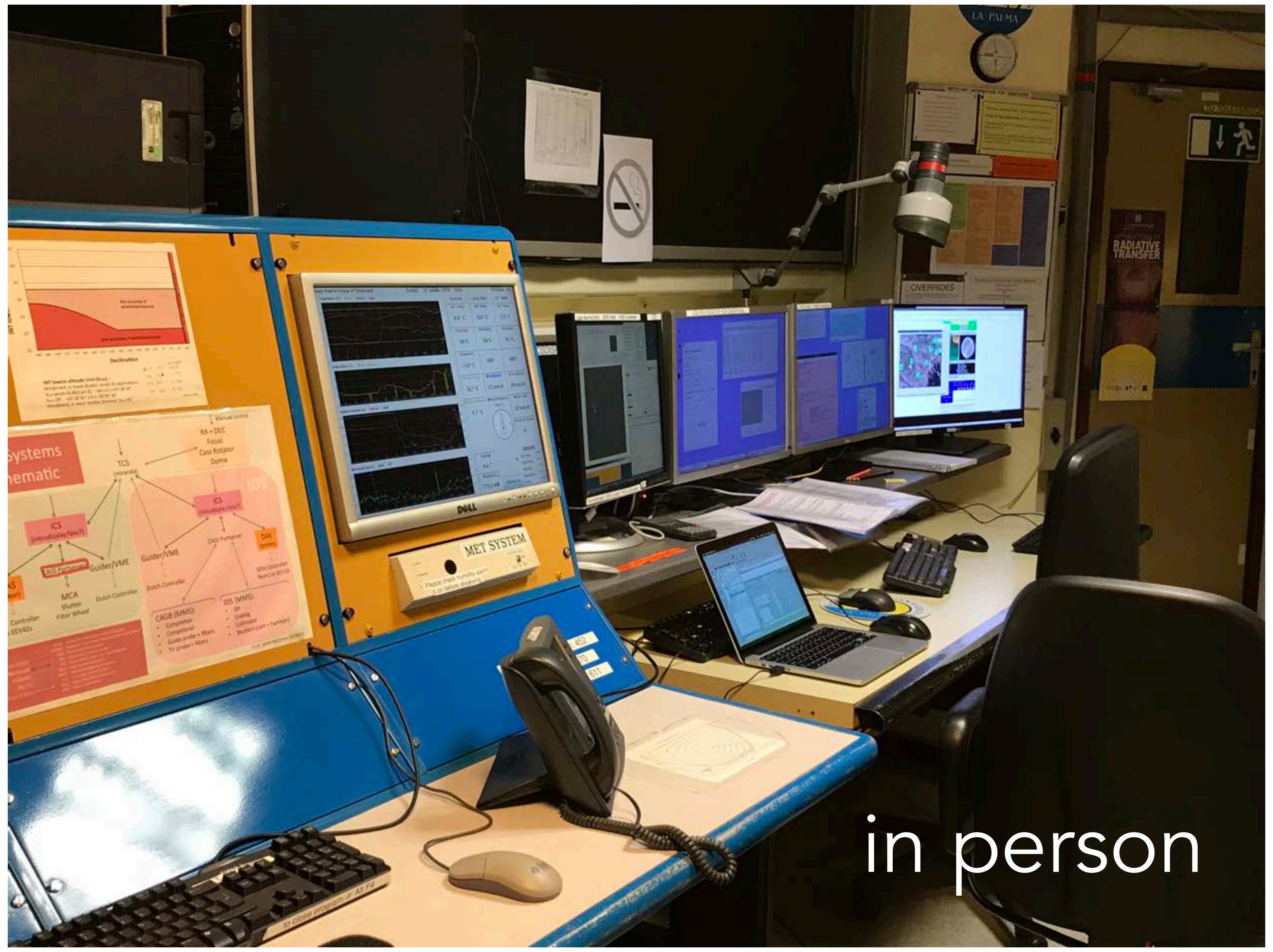
in person

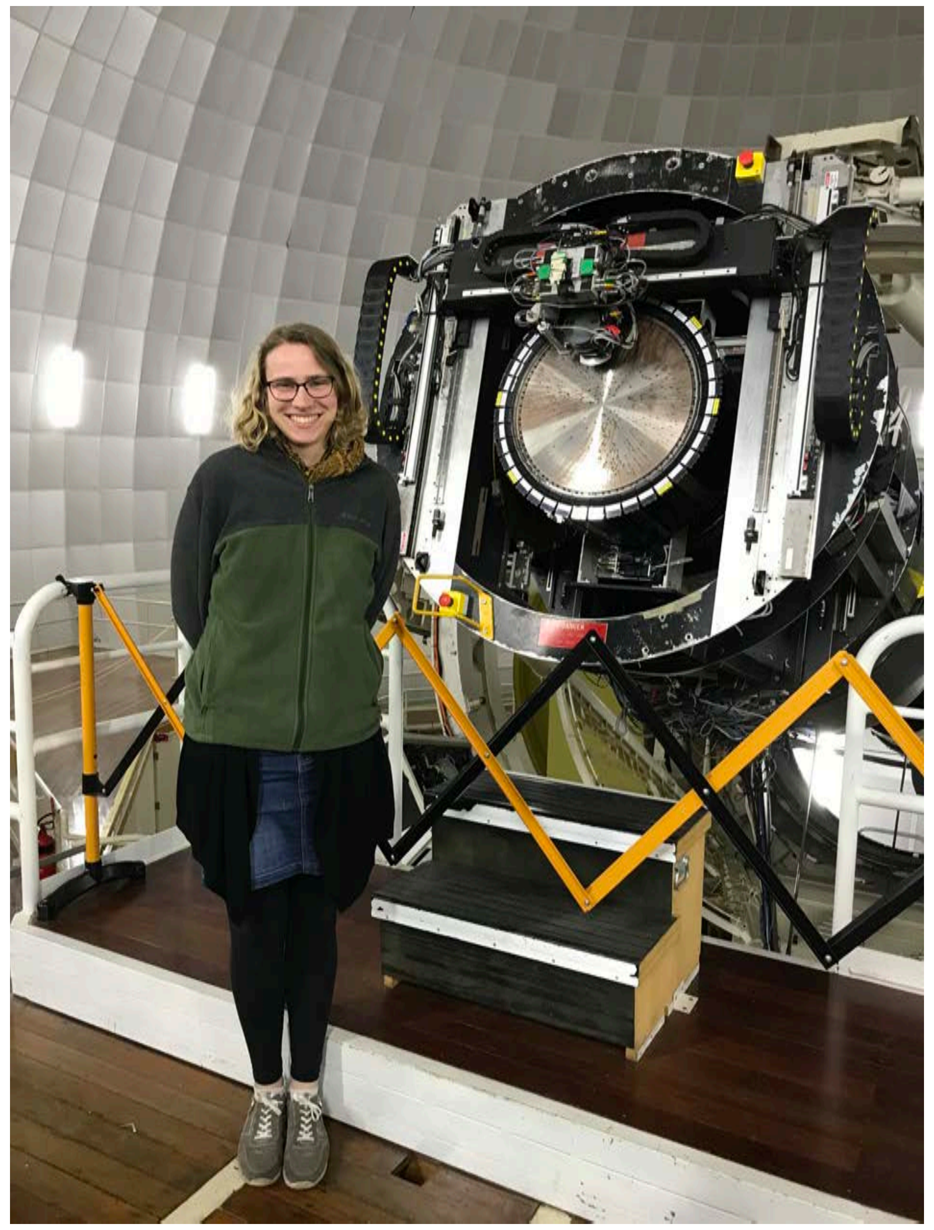


remotely
(with support)

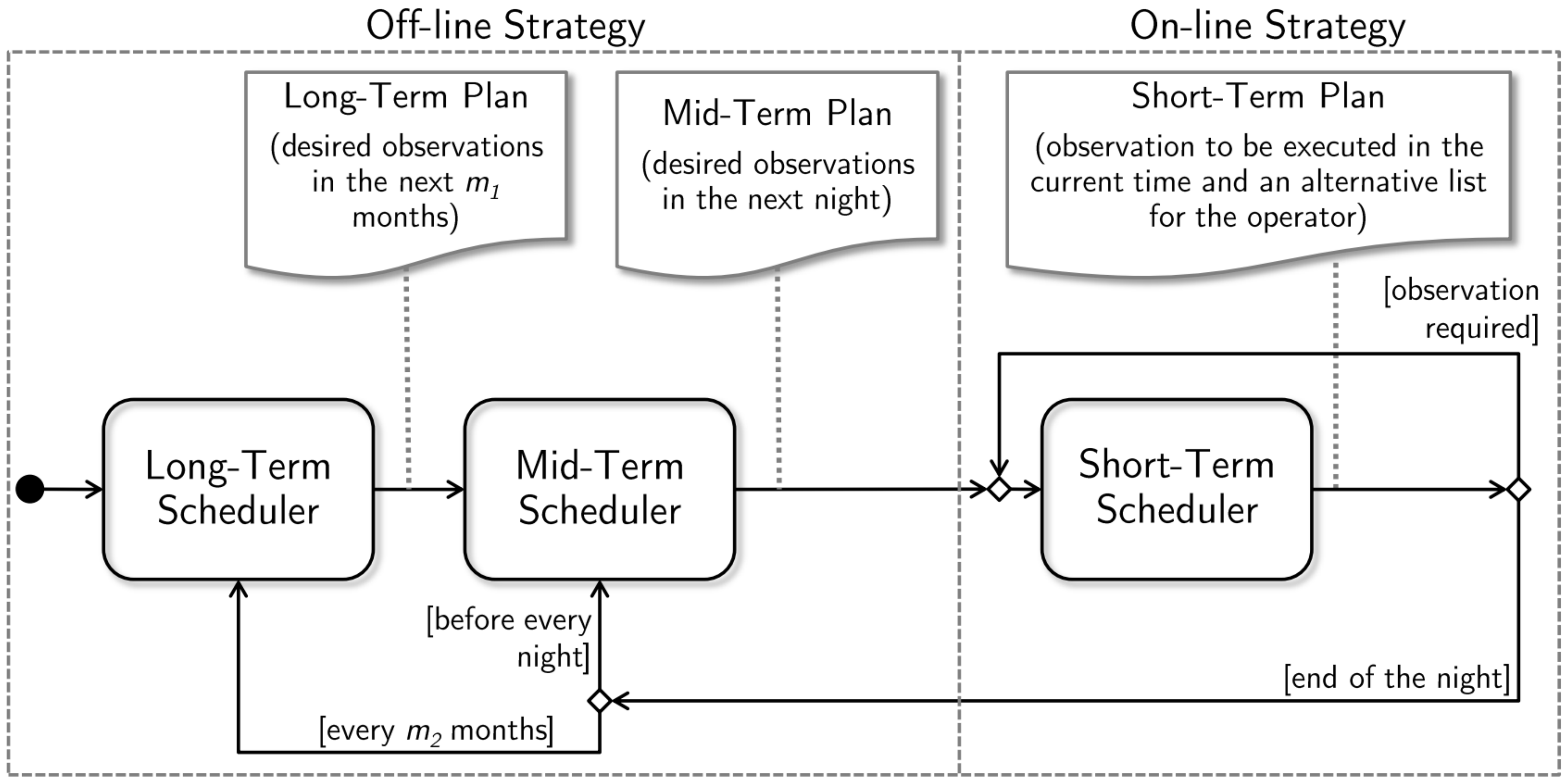
Observing

AAT





CFHT

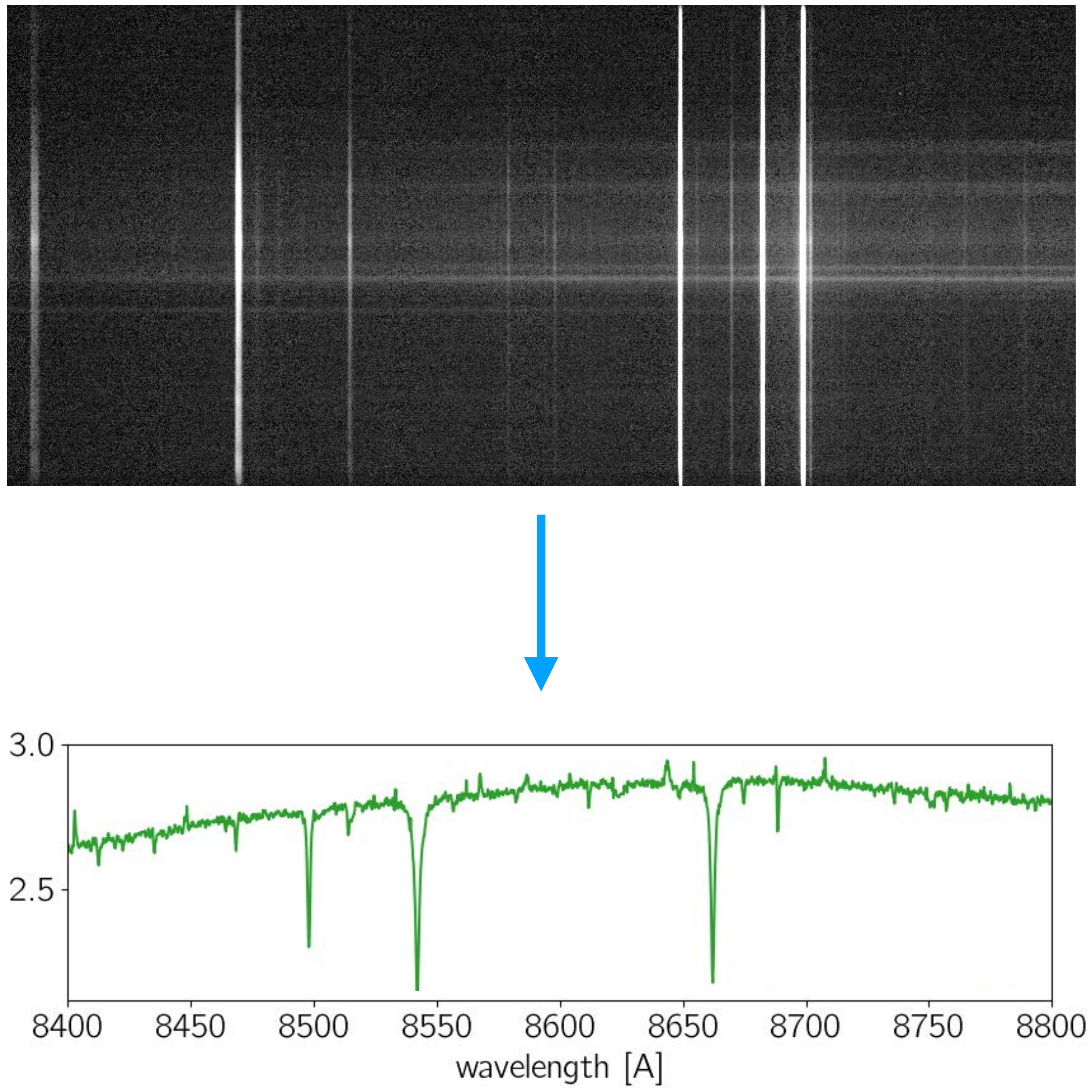


Queue observing

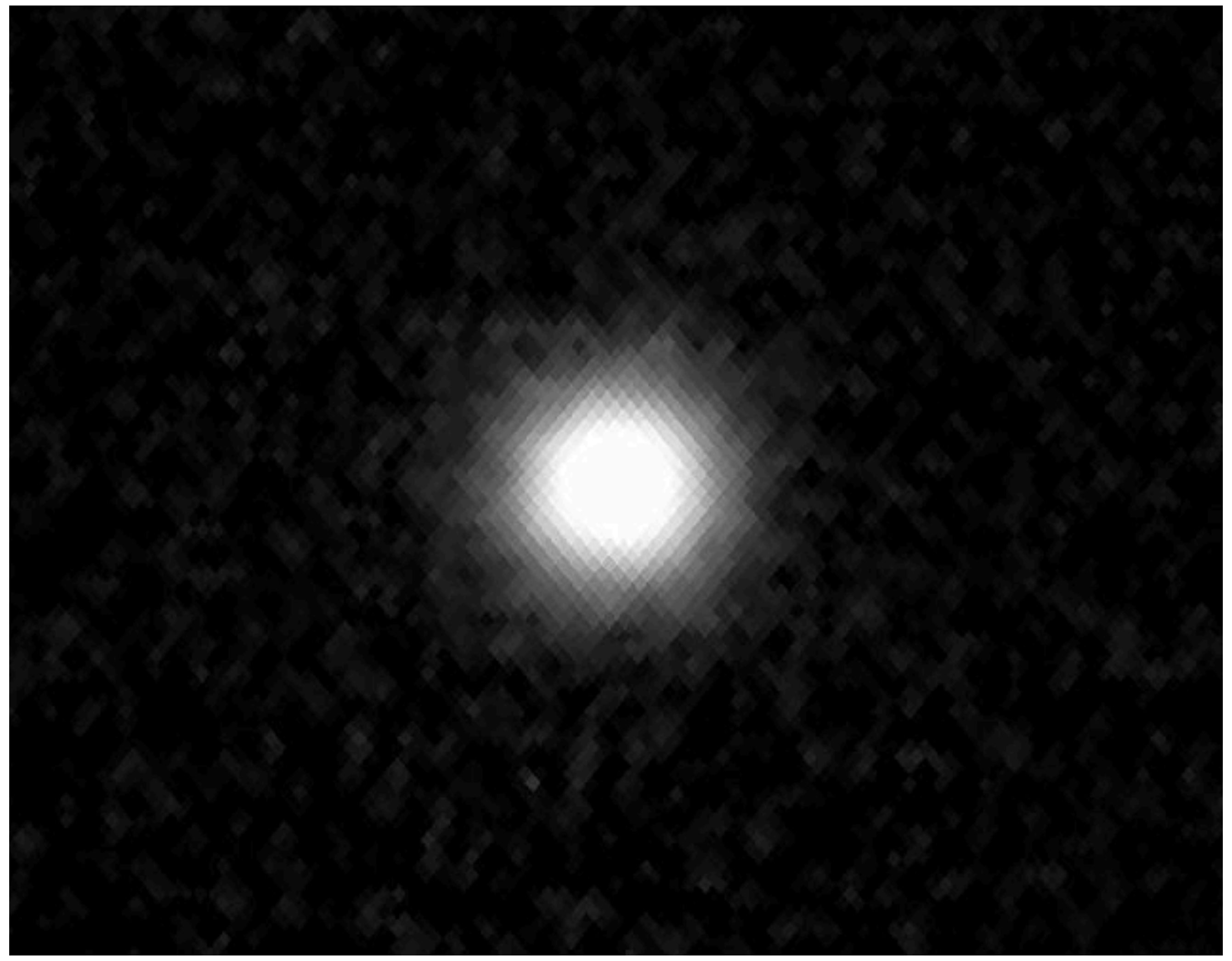
Process raw data

Data from the telescope is “raw”. Needs to be processed before use (using dedicated calibration observations), e.g. for spectra:

- Correct imperfections in camera/imaging system (“flat field”, “dark”, “bias”)
- Convert pixels —> wavelength (need “arcs”, a spectrum with known wavelengths)
- Remove background
  - “Sky” (not the object of interest)
  - “Telluric lines” (earth atmosphere)
- Extract spectrum from 2D image



Ready to analyse the data (PIGS): Step 1 — photometry



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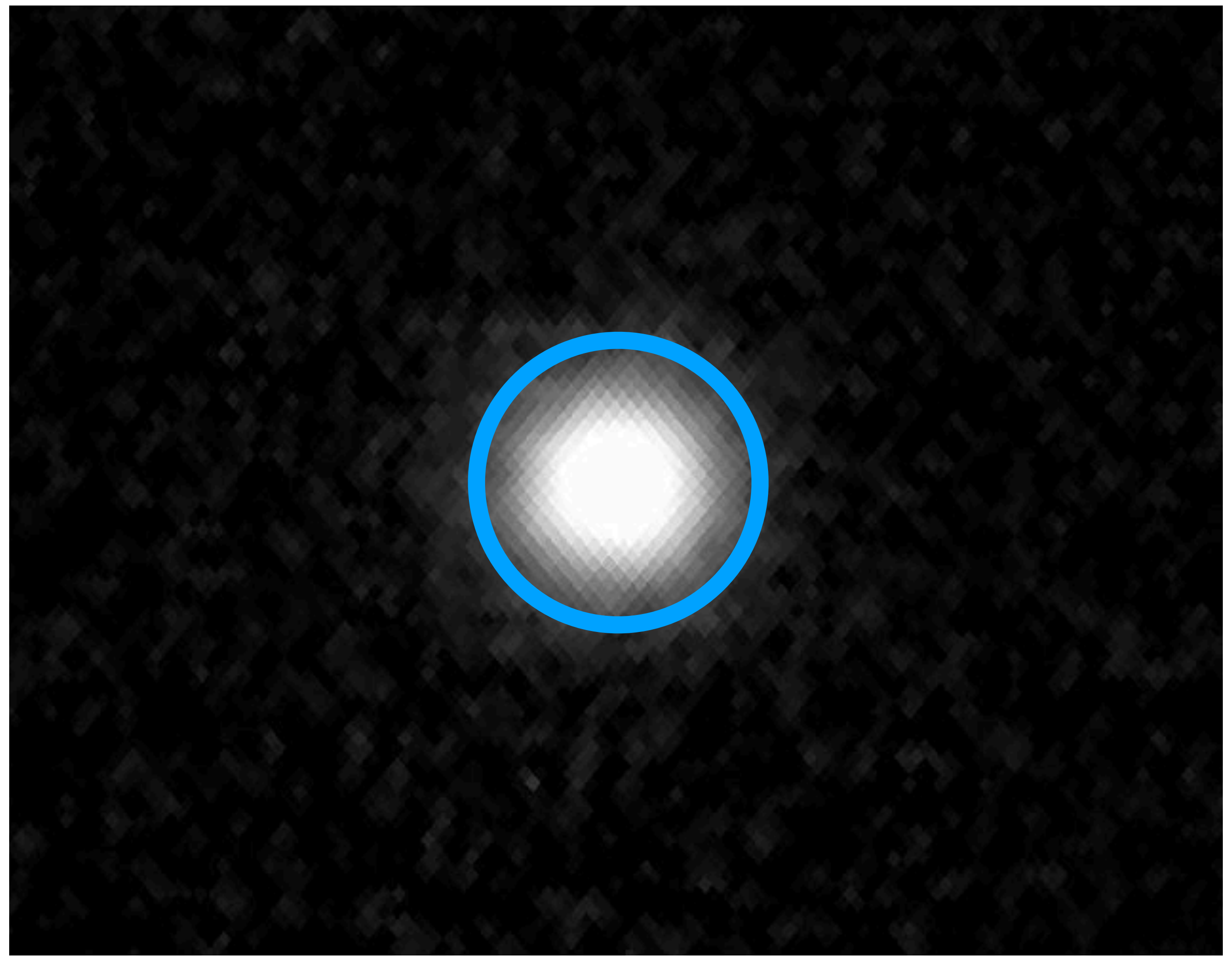
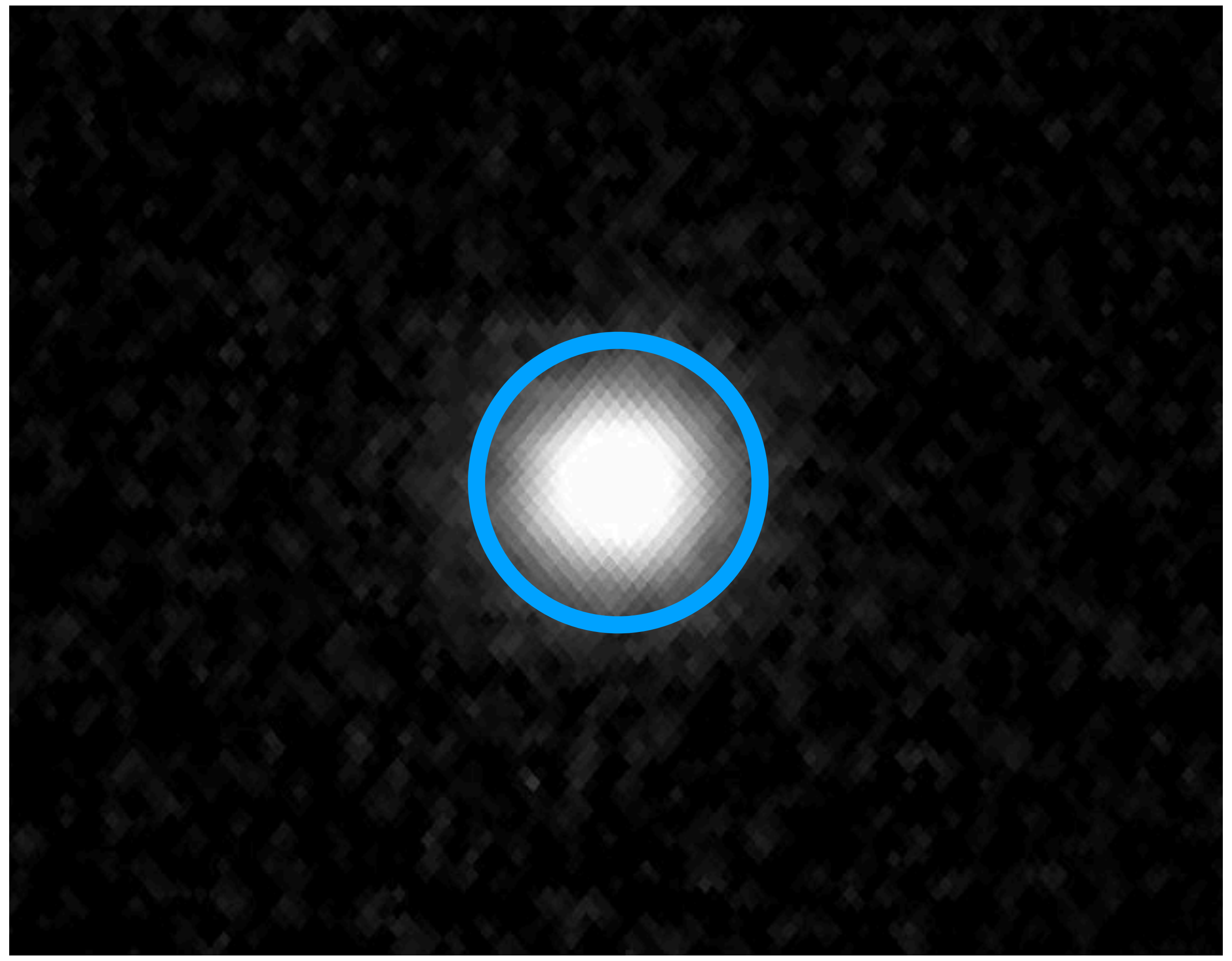


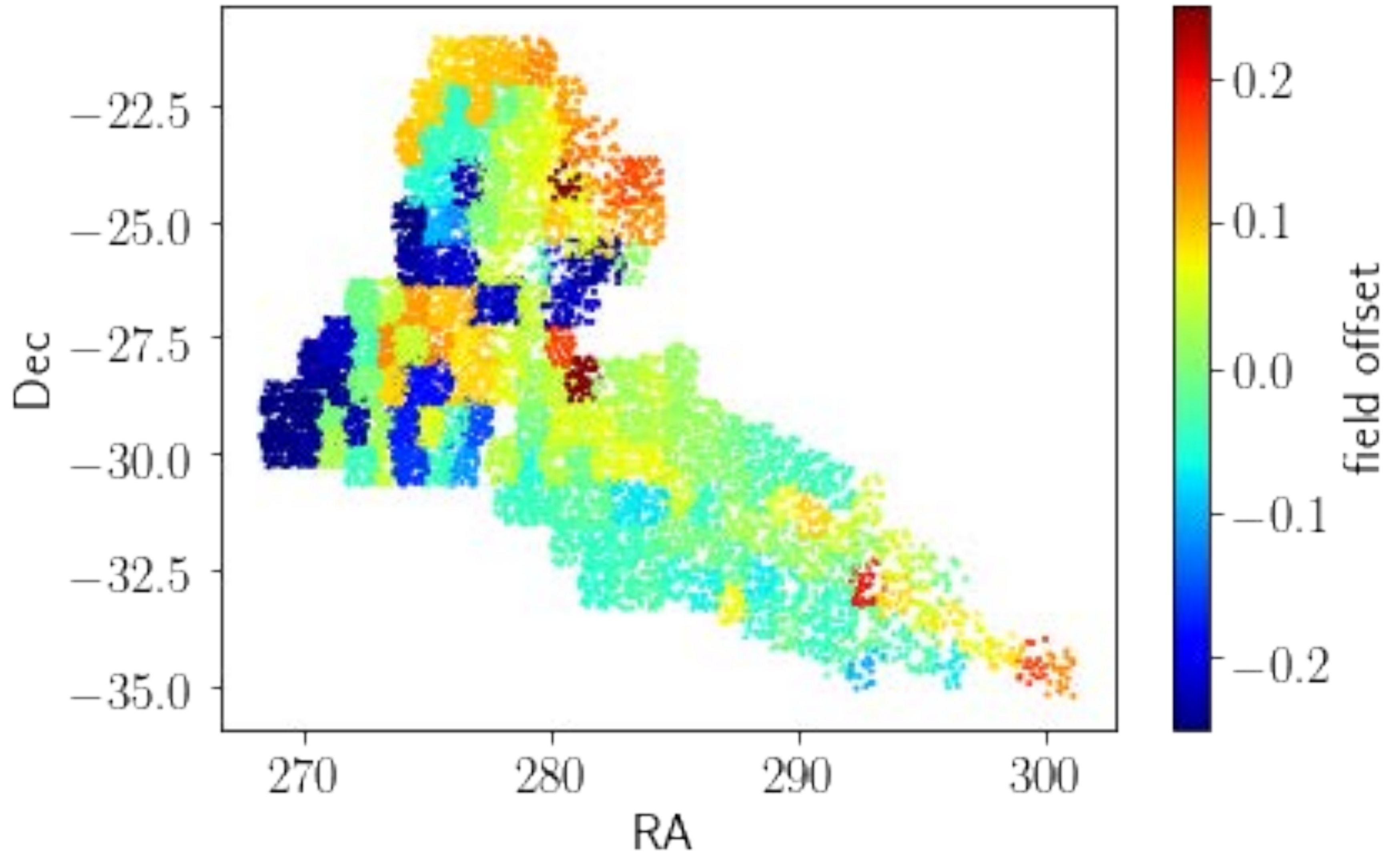
$$CaHK = -2.5 \log \frac{\text{flux in CaHK}}{\text{standard star flux(?)}}$$

Ready to analyse the data (PIGS): Step 1 — photometry



$$CaHK = -2.5 \log \frac{\text{flux in CaHK}}{\text{standard star flux(?)}}$$

- No "standard stars" in *CaHK*…
- Every observed field is on a slightly different scale…
  - Early method: use overlap between fields to get to a common scale (for PIGS only)
  - Now: use synthetic *CaHK* magnitudes from Gaia XP



Ready to analyse the data (PIGS): Step 1 — photometry

- Select best ~350 candidates in each field for follow-up spectroscopy
- Important: correcting for extinction!

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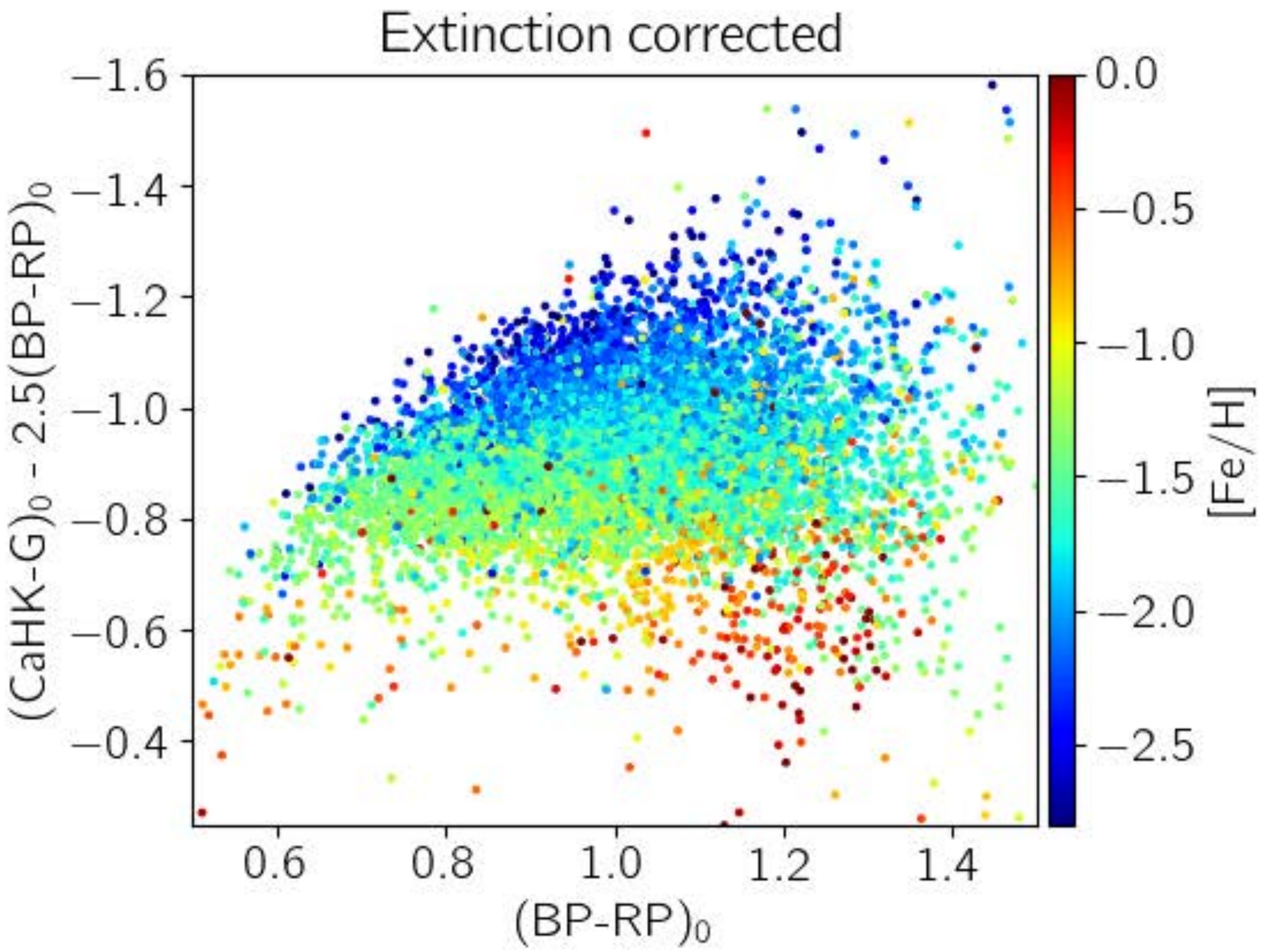

Ready to analyse the data (PIGS): Step 1 — photometry

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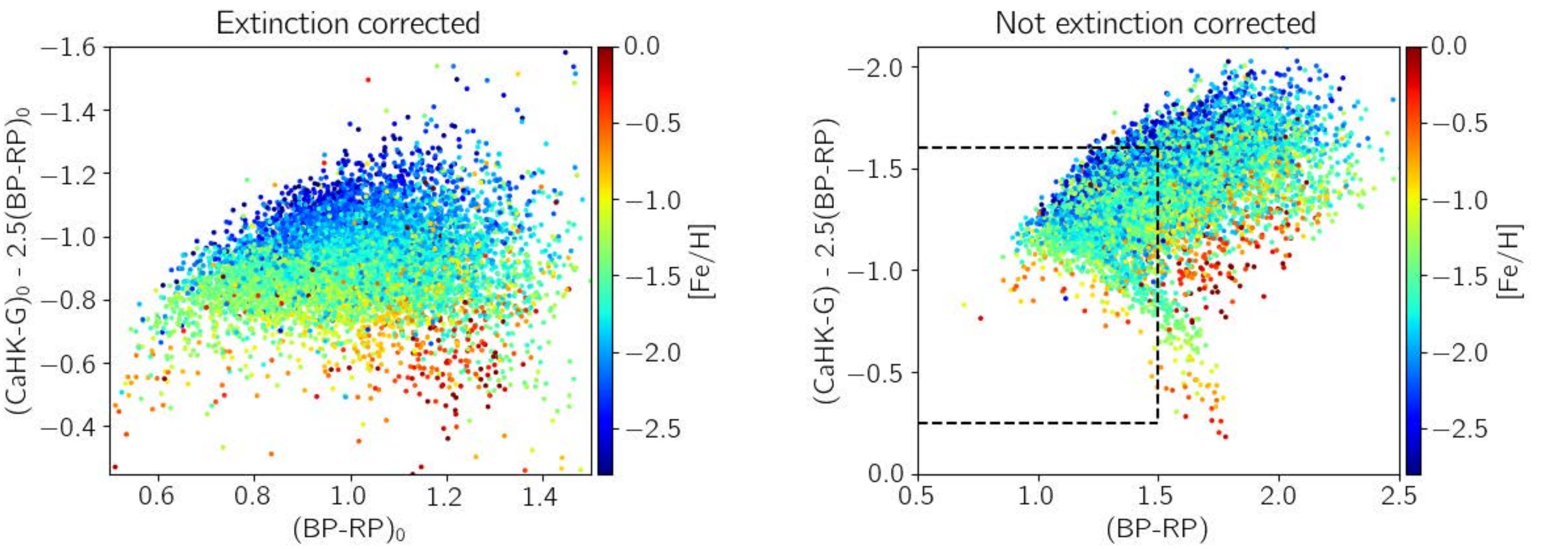
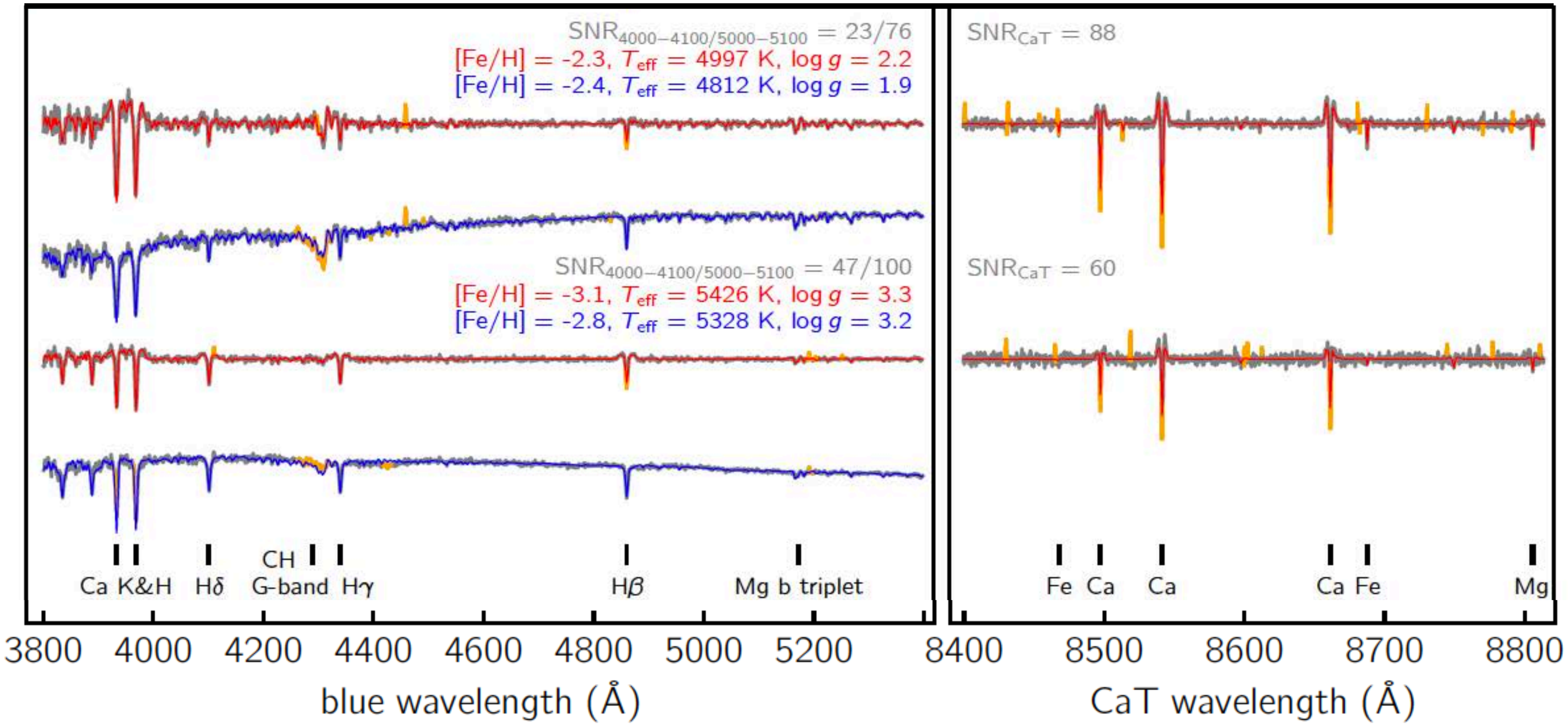


Ready to analyse the data (PIGS): Step 2 — spectroscopy

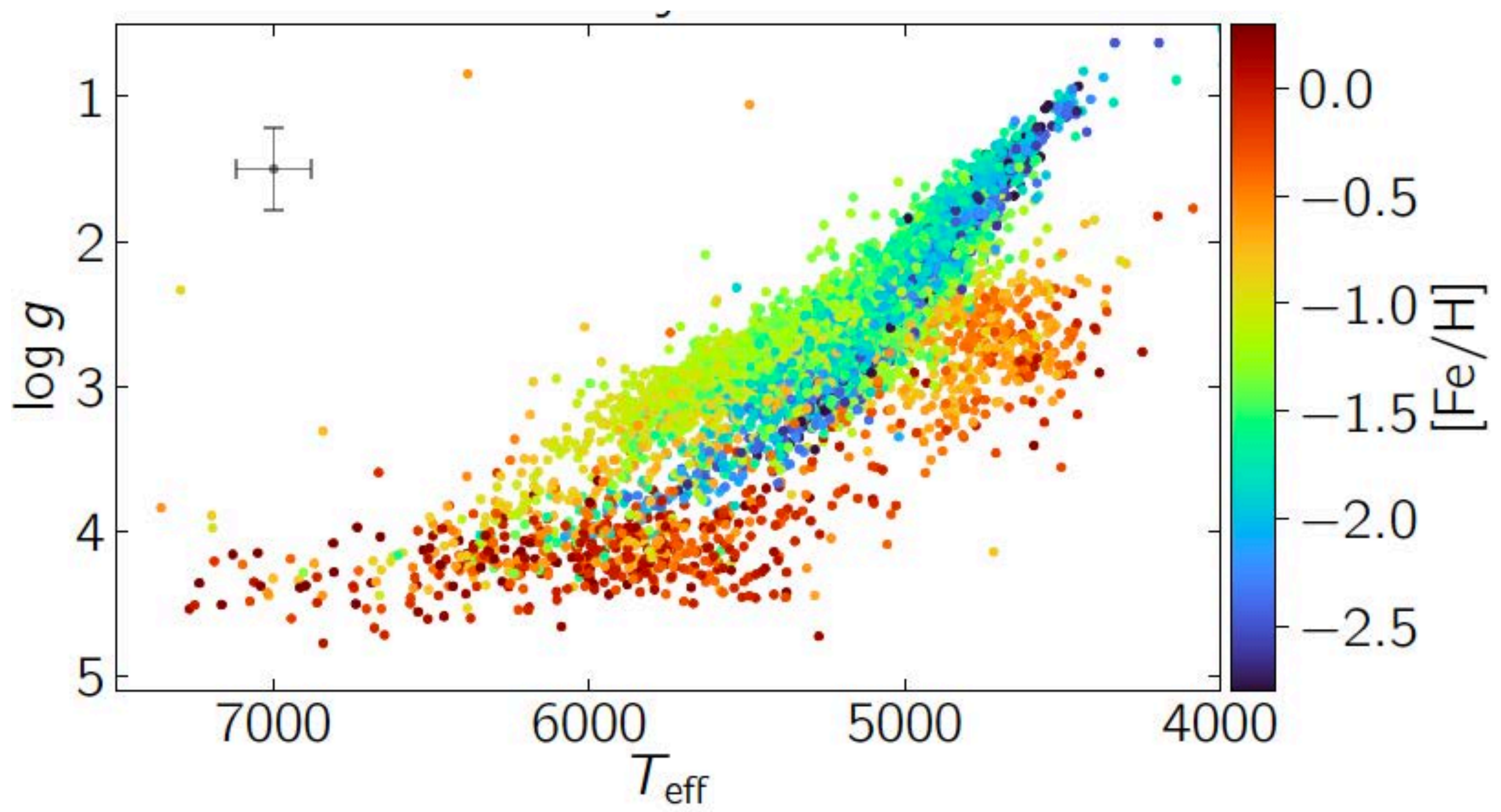
Two full-spectrum fitting methods, FERRE & ULySS, both minimising the chi square between the observed spectra & a reference library (necessary: interpolation!)

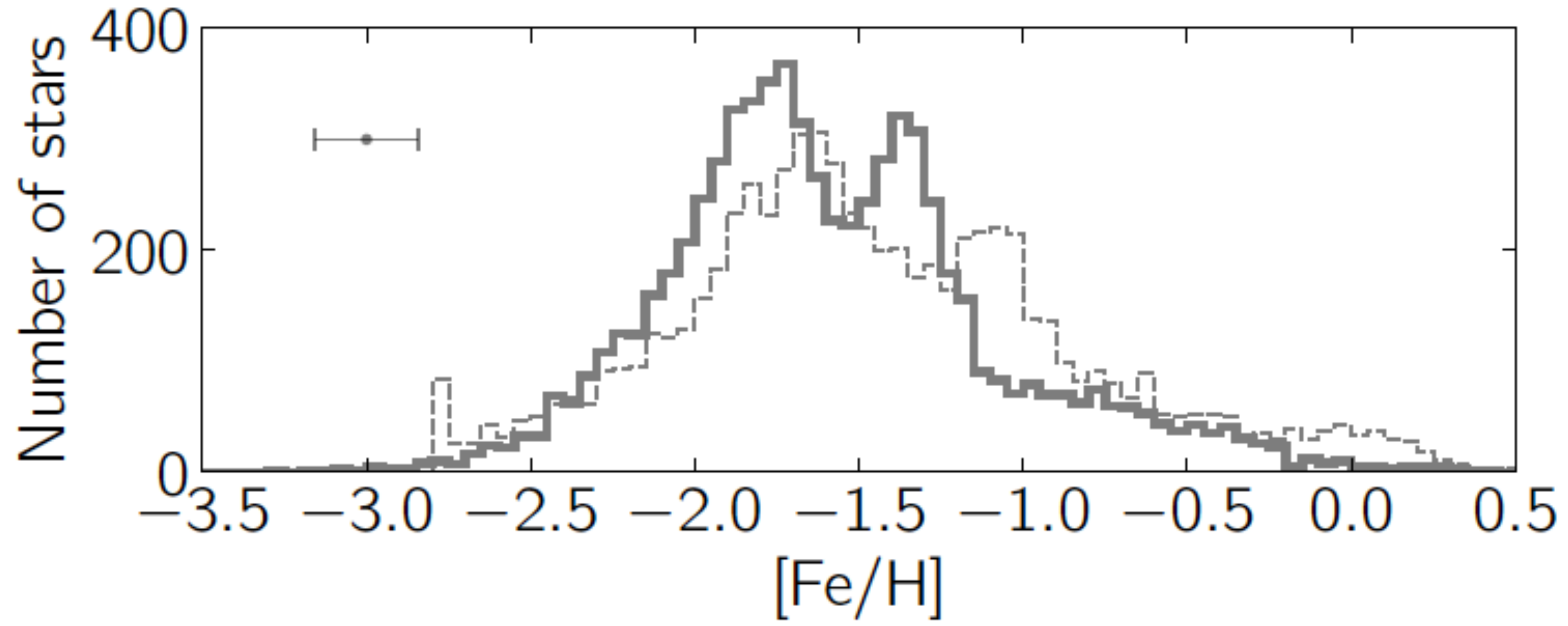


FERRE: synthetic model library, cubic interpolation between nodes, BTRK global optimisation

ULySS: empirical reference spectral library, using a polynomial interpolator

Ready to analyse the data (PIGS): Step 2 — spectroscopy





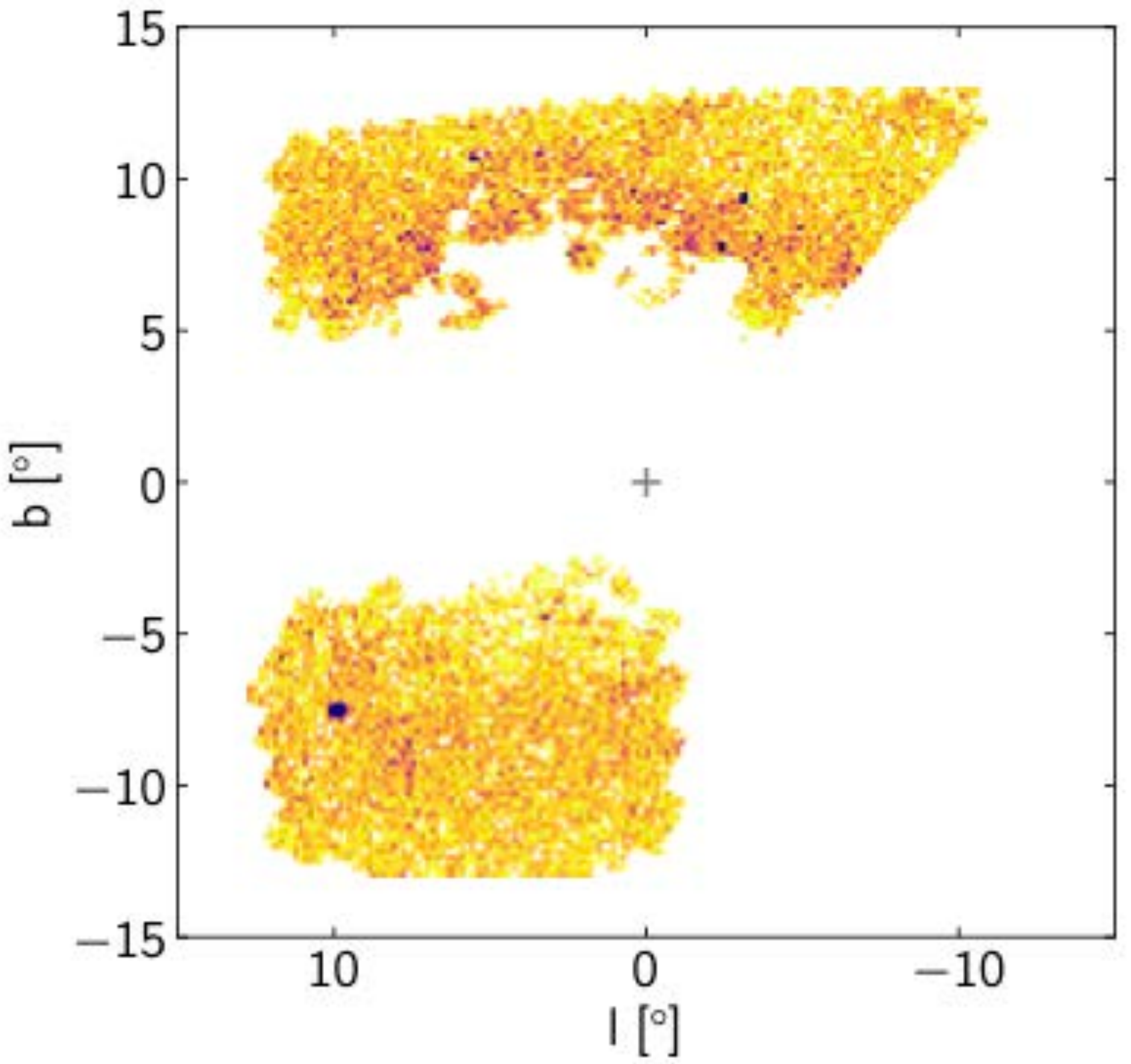
Write papers, and repeat the whole process…

- ➤ Next: more analysis, now “science-focused”
- ➤ Discuss with collaborators (none of this work was done alone!!)
- ➤ Write up the results in papers
- ➤ Sometimes you end up doing different/unexpected things from what you wrote in proposals!

What is the next step for PIGS?

- Follow-up was a bit inhomogeneous, and low-resolution so no abundances (except for carbon)
- What we really want is many stars, homogeneously observed, with abundances, analysed on a common scale with other stars!
- How? 4MOST: upcoming multi-object spectrograph, survey starting in 2026

30 000 PIGS stars with photometric [Fe/H] < −1.7



4MOST will have >2000 fibres per pointing
and will observe millions of stars & galaxies over 5 years

How are large surveys/projects different?

The typical observing cycle

- Idea/research question
- What kind of observations do I need? Which facility can provide these?
- Write a telescope proposal
  - Scientific justification
  - Technical justification
- If accepted:
  - prepare for observations
  - do the observations (your team or telescope operators)
  - get the raw data, next step: analyse

A large survey

- Many ideas/research questions around various themes, but the same instrument/facility
- What kind of observations do we need? Need to build a new facility/instrument/mission?
- Write a project proposal (often >100s pages), “white paper”, funding proposals
  - Scientific justification
  - Technical justification
  - Financial justification!
- If accepted:
  - prepare & plan for observations (often over multiple years)
  - make sure observations run smoothly
  - get the raw data, reduce, analyse, quality control & release the data

Usually a HUGE team effort!

The *Gaia* mission★

(first Gaia paper with DR1)

Gaia Collaboration, T. Prusti[1,★★], J. H. J. de Bruijne[1], A. G. A. Brown[2], A. Vallenari[3], C. Babusiaux[4], C. A. L. Bailer-Jones[5], U. Bastian[6], M. Biermann[6], D. W. Evans[7], L. Eyer[8], F. Jansen[9], C. Jordi[10], S. A. Klioner[11], U. Lammers[12], L. Lindegren[13], X. Luri[10], F. Mignard[14], D. J. Milligan[15], C. Panem[16], V. Poinsignon[17], D. Pourbaix[18,19], S. Randich[20], G. Sarri[21], P. Sartoretti[4], H. I. Siddiqui[22], C. Soubiran[23], V. Valette[16], F. van Leeuwen[7], N. A. Walton[7], C. Aerts[24,25], F. Arenou[4], M. Cropper[26], R. Drimmel[27], E. Høg[28], D. Katz[4], M. G. Lattanzi[27], W. O'Mullane[12], E. K. Grebel[6], A. D. Holland[29], C. Huc[16], X. Passot[16], L. Bramante[30], C. Cacciari[31], J. Castañeda[10], L. Chaoul[16], N. Cheek[32], F. De Angeli[7], C. Fabricius[10], R. Guerra[12], J. Hernández[12], A. Jean-Antoine-Piccolo[16], E. Masana[10], R. Messineo[30], N. Mowlavi[8], K. Nienartowicz[33], D. Ordóñez-Blanco[33], P. Panuzzo[4], J. 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Gaia Data Release 3

Summary of the content and survey properties

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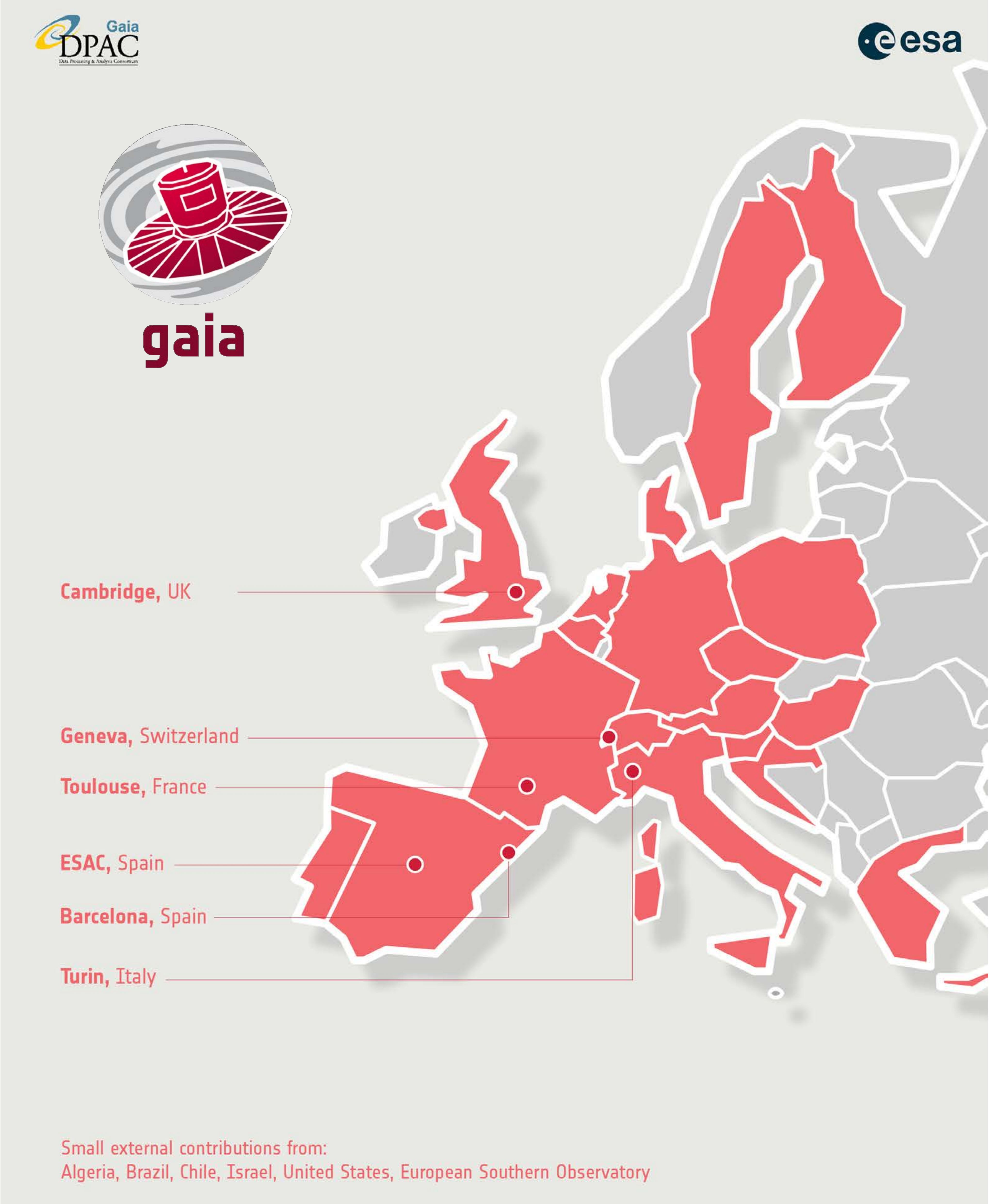
J. Zorec[146], S. Zucker[71], and T. Zwitter[147]

(Affiliations can be found after the references)

Gaia DPAC (Data Processing and Analysis Consortium) has > 450 members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esa
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Cambridge, UK
Geneva, Switzerland
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ESAC, Spain
Barcelona, Spain
Turin, Italy
Small external contributions from:
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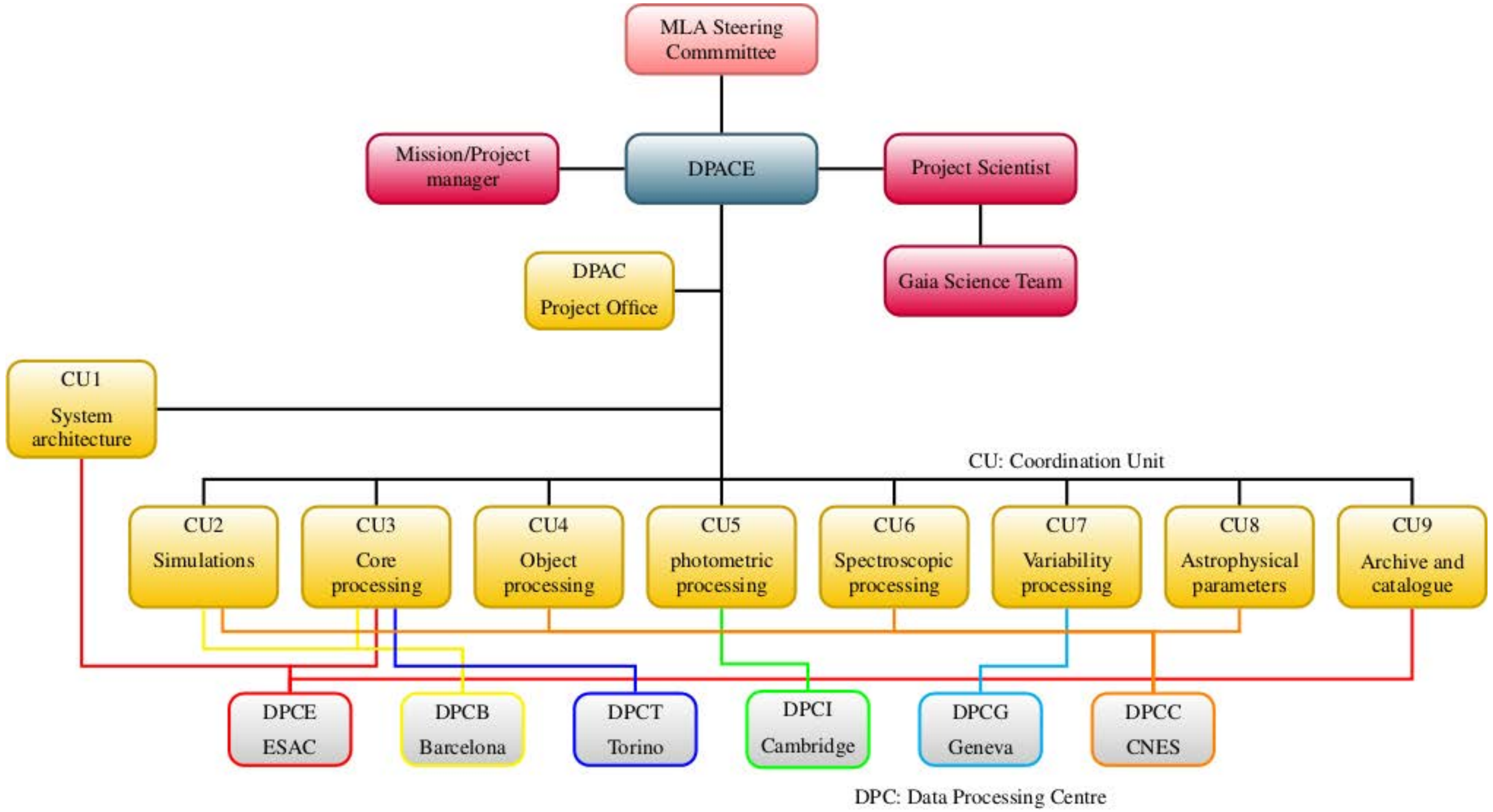
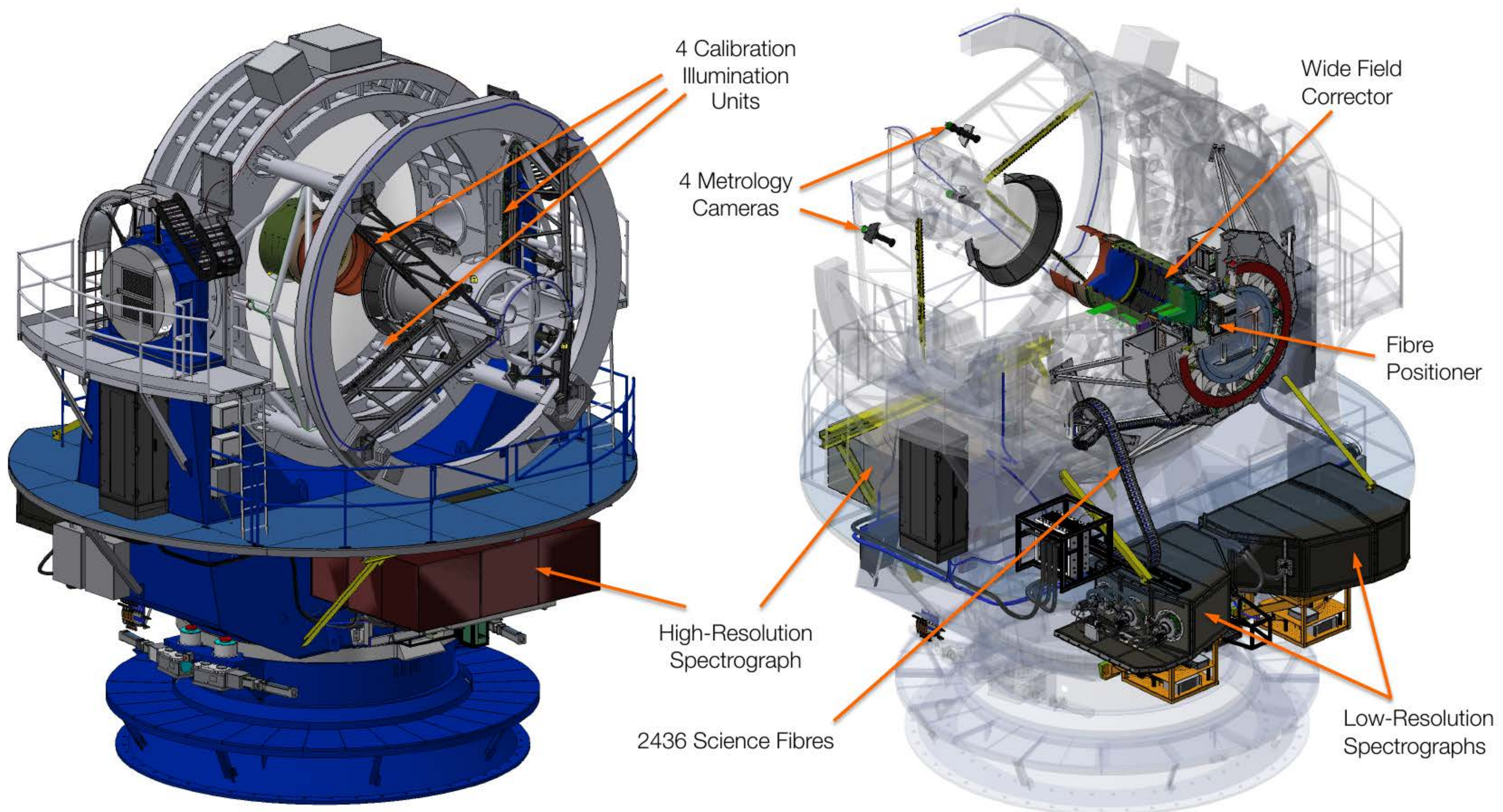
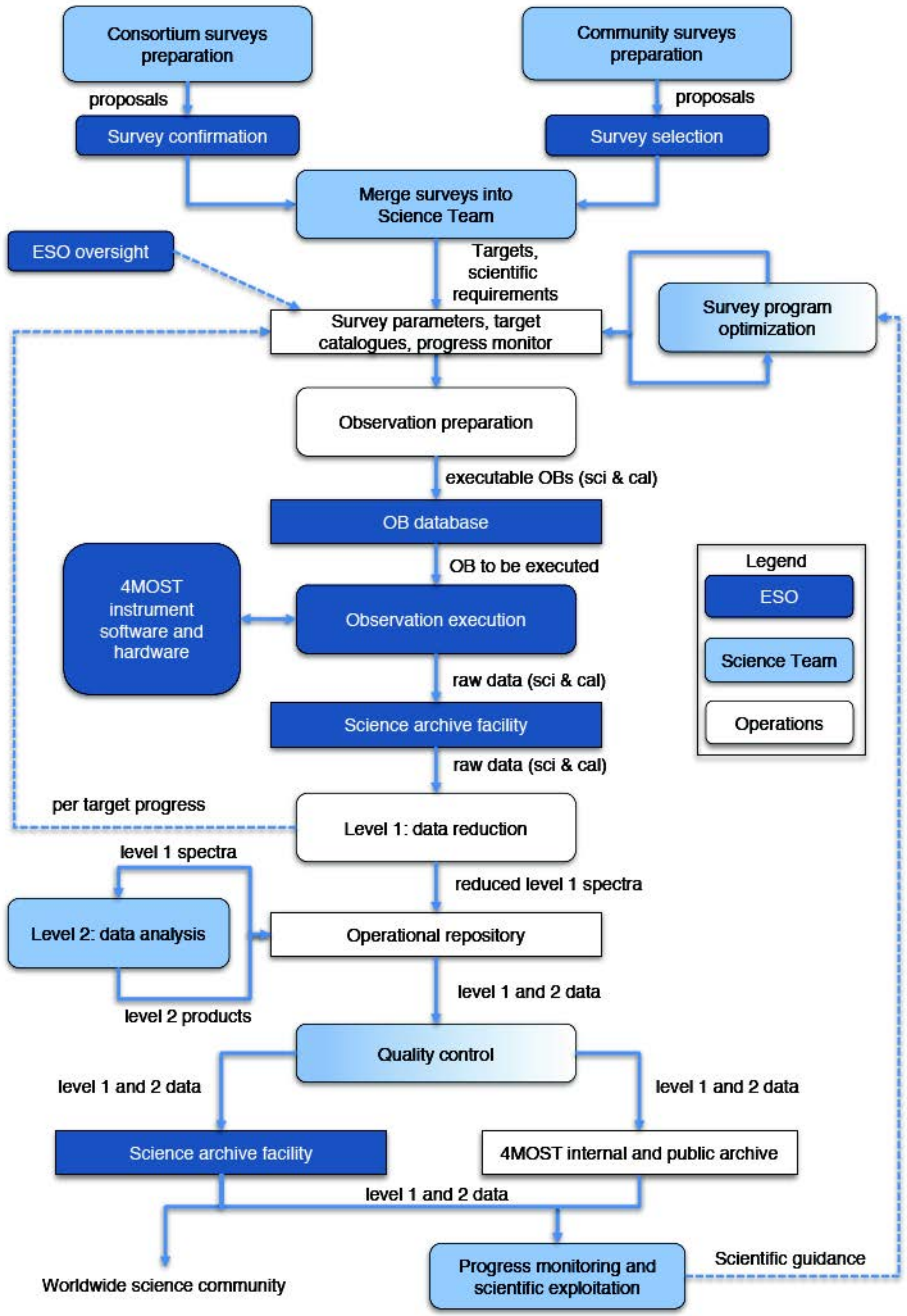

MLA Steering Commmittee
Mission/Project manager
DPACE
Project Scientist
Gaia Science Team
DPAC Project Office
CU1 System architecture
CU: Coordination Unit
CU2 Simulations
CU3 Core processing
CU4 Object processing
CU5 photometric processing
CU6 Spectroscopic processing
CU7 Variability processing
CU8 Astrophysical parameters
CU9 Archive and catalogue
DPCE ESAC
DPCB Barcelona
DPCT Torino
DPCI Cambridge
DPCG Geneva
DPCC CNES
DPC: Data Processing Centre

4MOST

- 700-800 people!
- Engineers (hardware & software), scientists (senior & postdoc/PhD), managers, operators…





Large dataset analysis & quality control

- Need to have a generic way of analysing all the data (starting to include ML pipelines)
- Often does not work well for oddballs!
- Usually projects provide some type of "quality control", including documentation on how to use the data **(read it!)**

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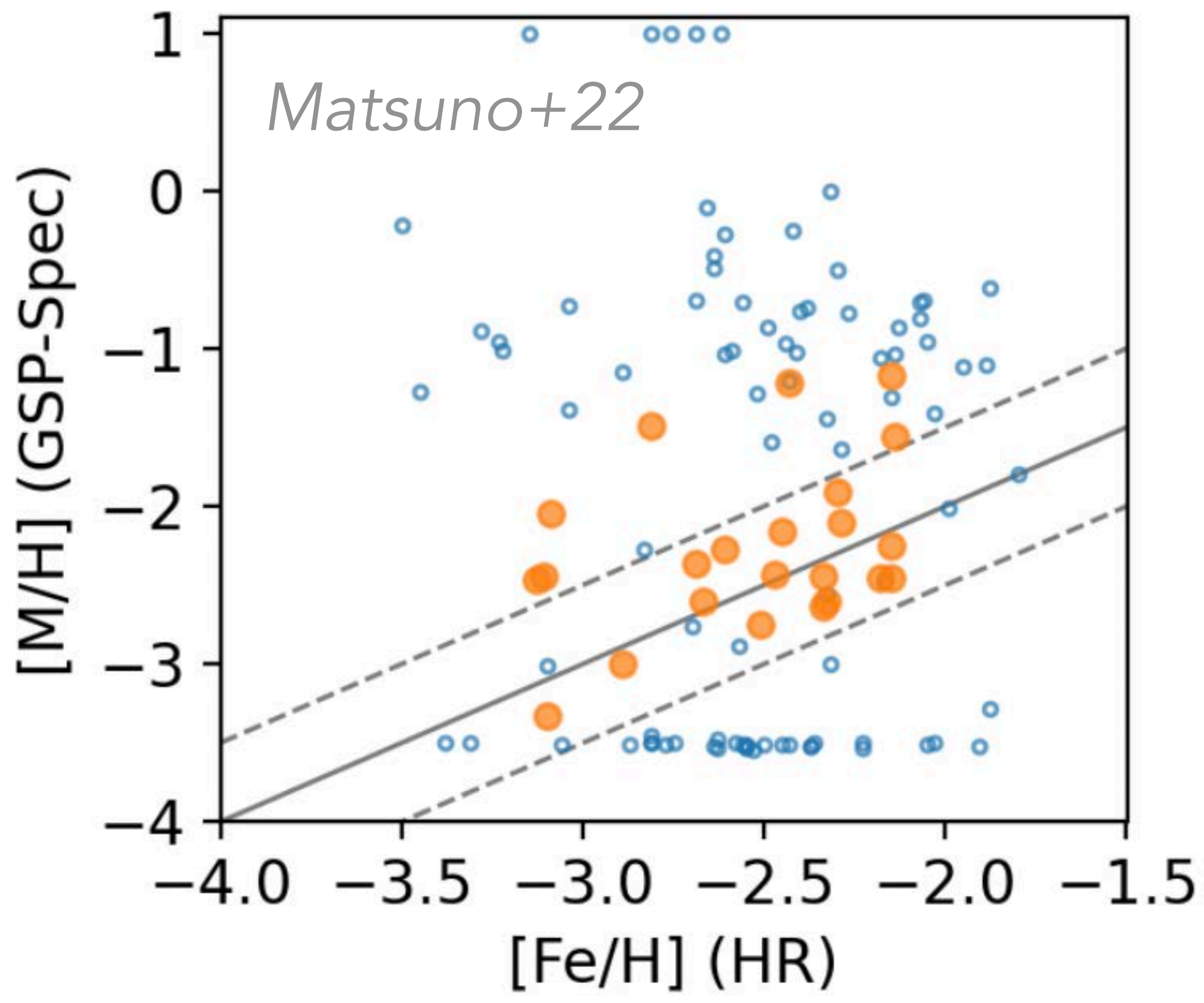

Sample of known VMP stars with Gaia RVS metallicities

Orange = recommended Gaia quality cuts

Large dataset analysis & quality control

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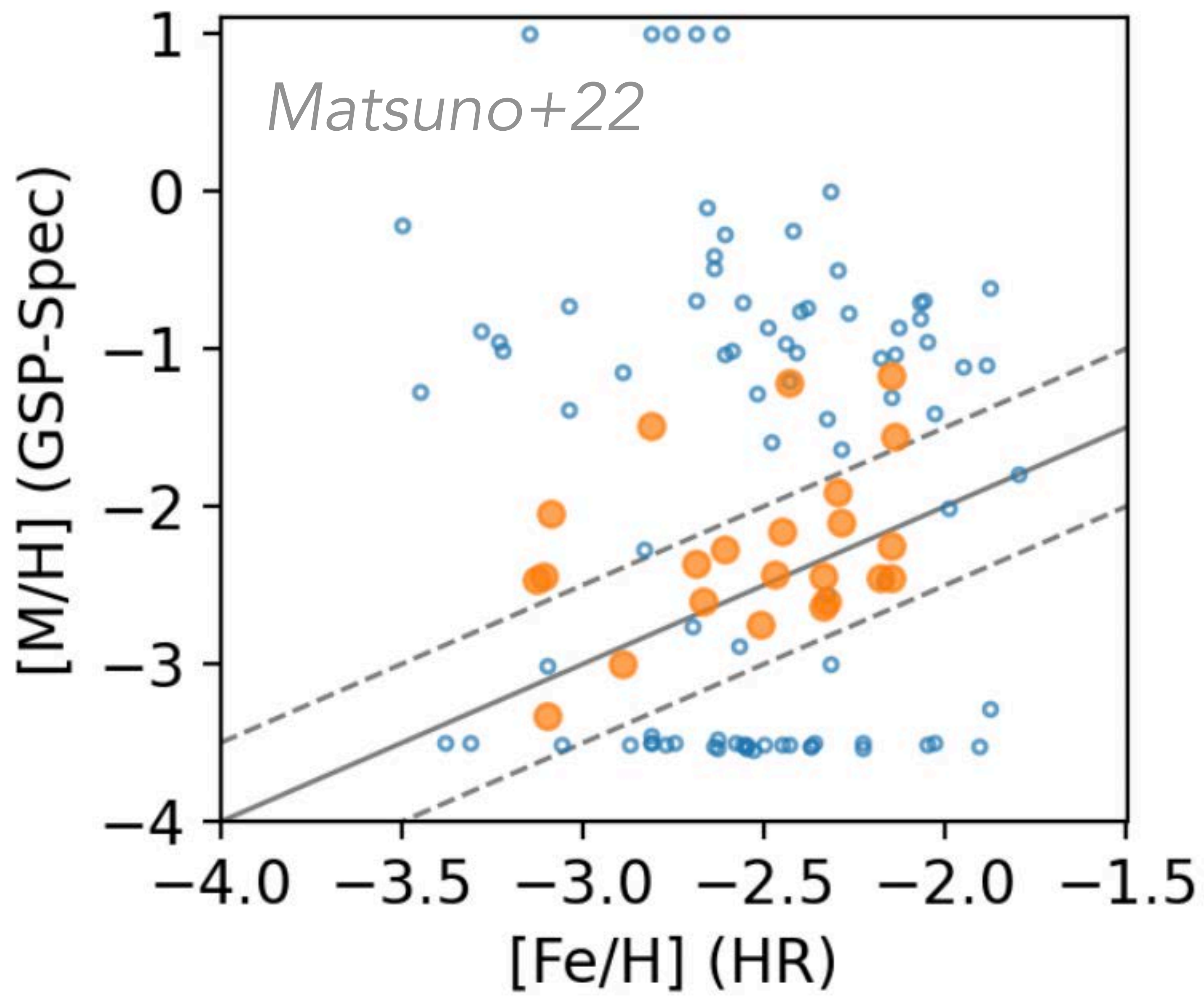

Sample of known VMP stars with Gaia RVS metallicities

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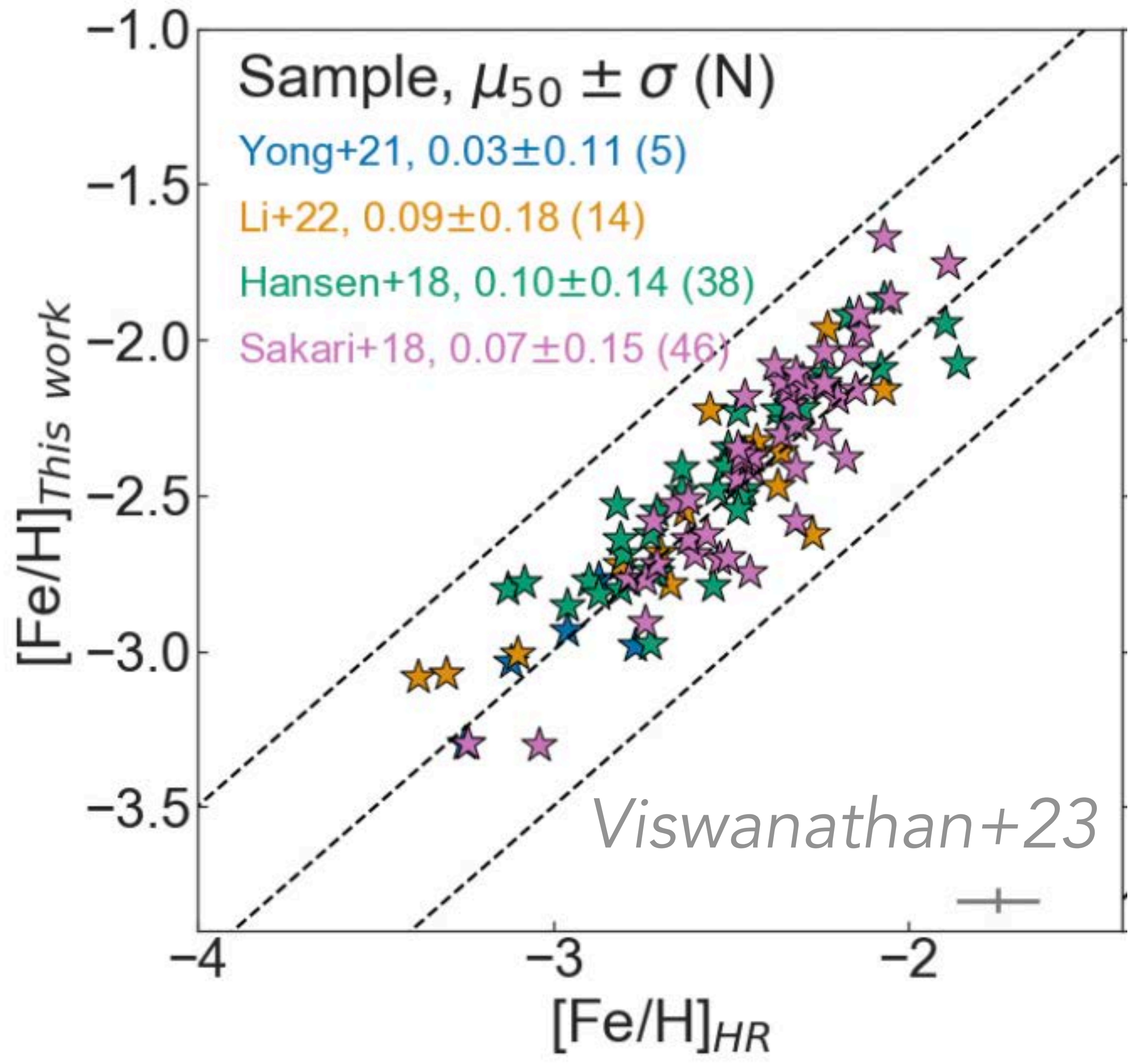
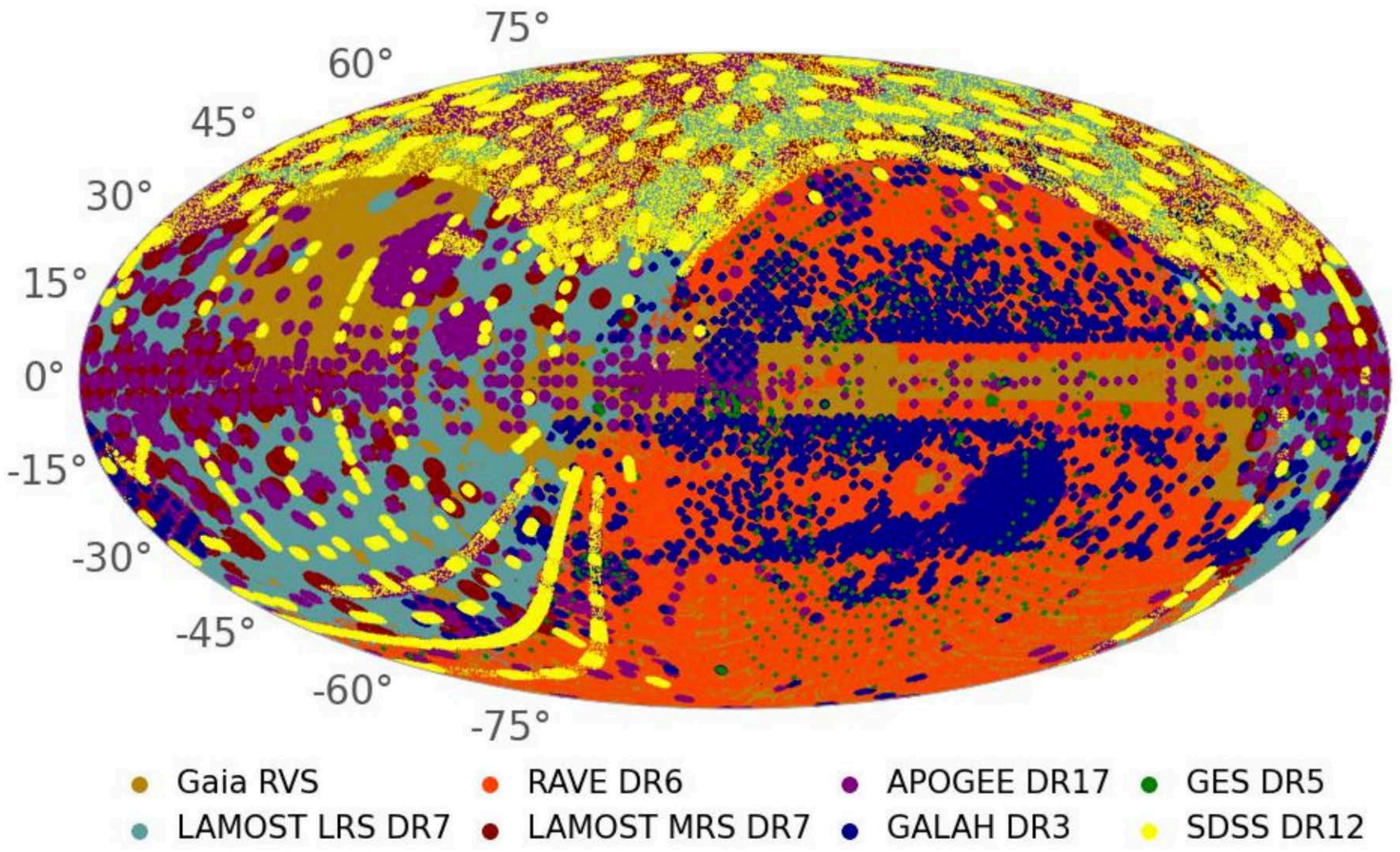
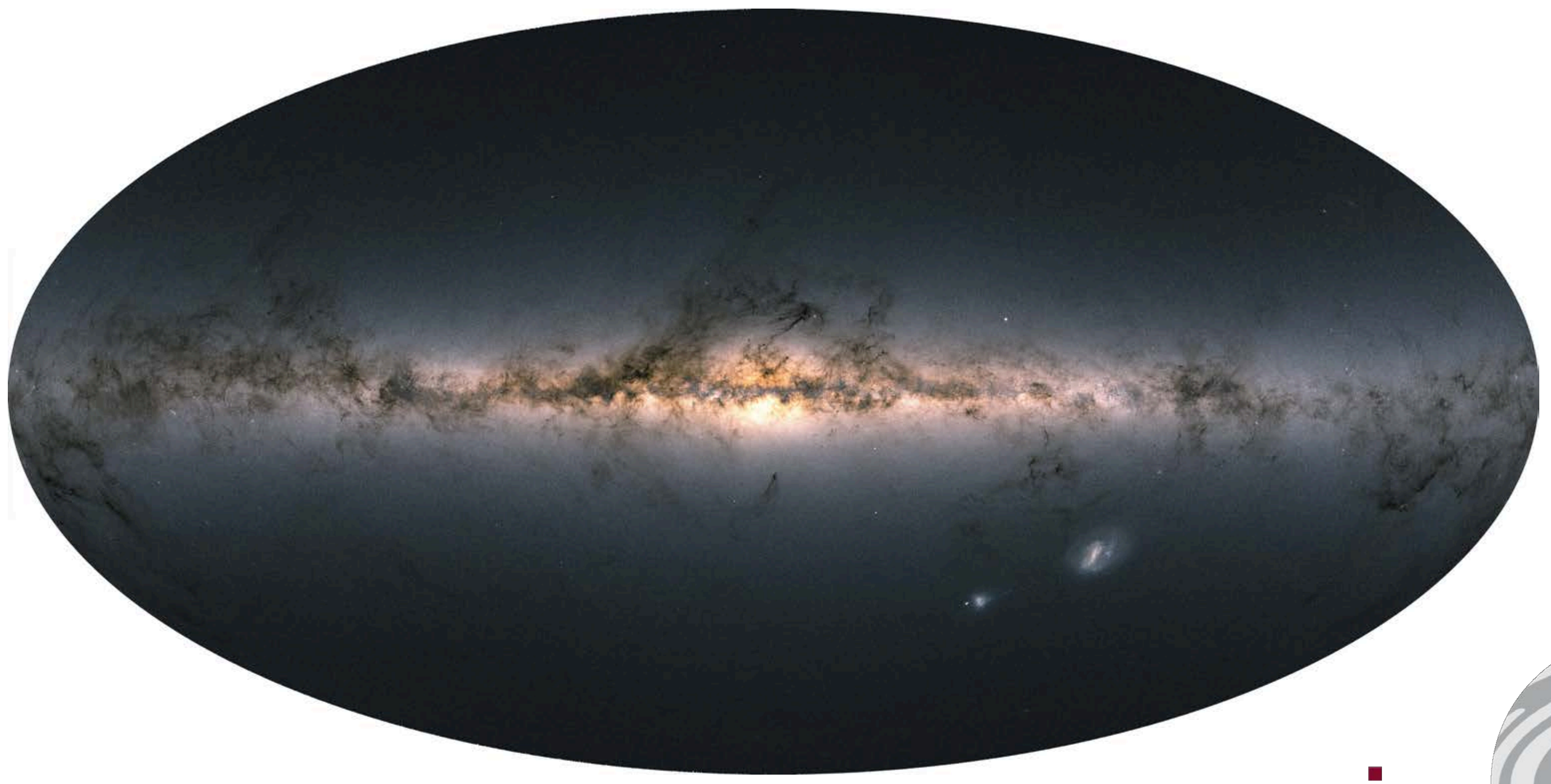


Dedicated analysis of Gaia RVS spectra

Summary

- A lot of work goes into building astronomical datasets, and providing them to the community
- Things could go wrong at various levels, so always be sceptical of "crazy" data!





gaia

Next lectures

- Tuesday: part recent results & part hands-on, bring your laptop if you can
  - Download material beforehand if possible (no need to do anything before the lecture, except maybe check needed Python packages: astropy, sklearn, umap)
  - Via the Notebooks sub-folder on Moodle, with a link to the data inside the notebook (Lecture6_hands-on_Gaia-RVS.ipynb)

- Next four lectures: **Dr GyuChul Myeong** on the Milky Way and Galactic dynamics
- Four lectures after that: **Dr Elisabeth Sola** on galaxy evolution in the Local Universe (beyond the Milky Way), image analysis