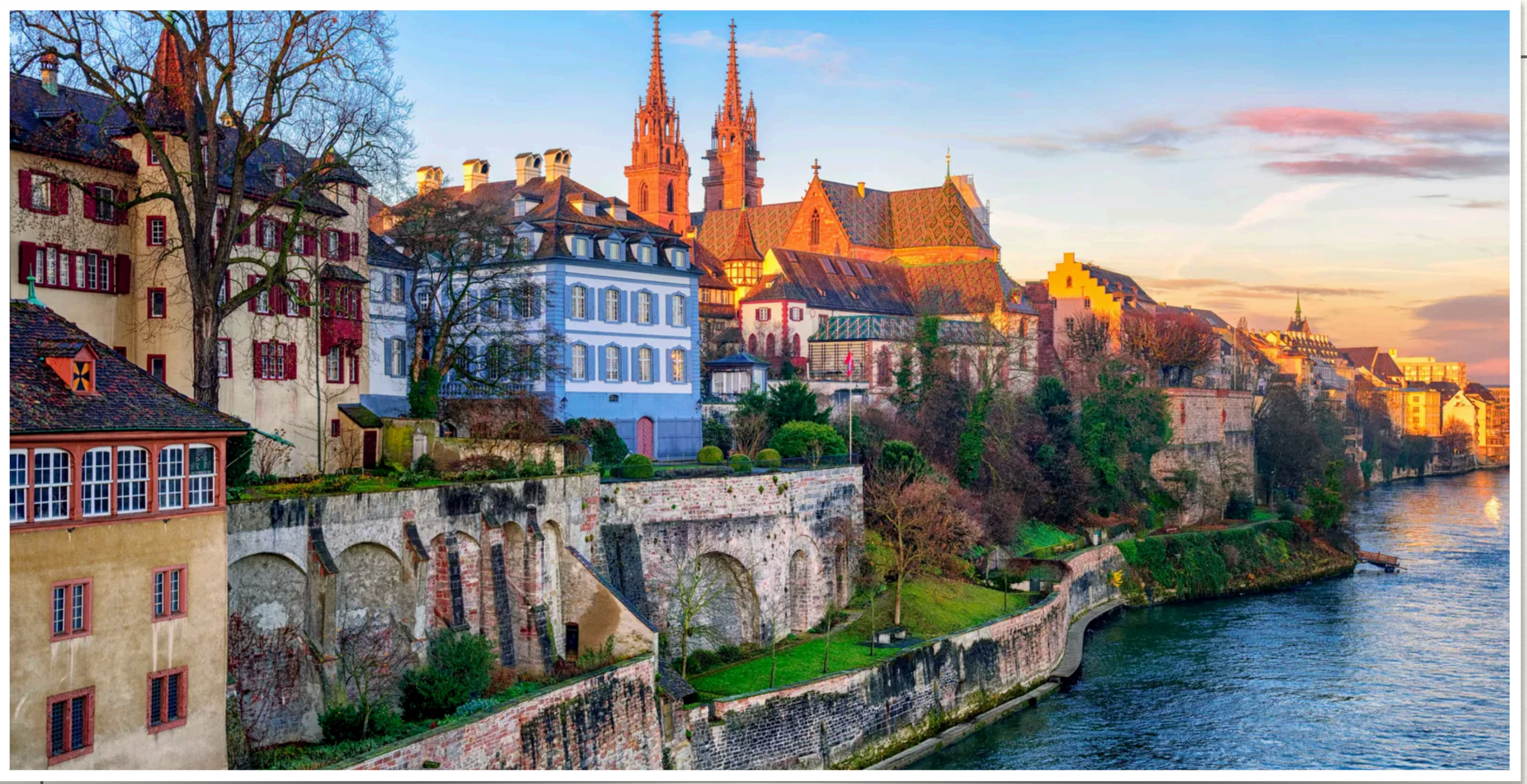
Ken Freeman @ 80 — The University of Western Australia

The Subaru Prime Focus Spectrograph Survey in the Milky Way and Local Group galaxies

Borja Anguiano
Notre Dame Department of Physics & Astronomy

RAVE meeting 2007



The New Galaxy: Signatures of Its Formation

Ken Freeman
Mount Stromlo Observatory, Australia National University, Weston Creek, ACT 2611, Australia; email: kcf@mso.anu.edu.au

Joss Bland-Hawthorn
Anglo-Australian Observatory, 167 Vimiera Road, Eastwood, NSW 2122, Australia; email: jbh@aao.gov.au

Key Words cosmology, local group, stellar populations, stellar kinematics

■ **Abstract** The formation and evolution of galaxies is one of the great outstanding problems of astrophysics. Within the broad context of hierachical structure formation, we have only a crude picture of how galaxies like our own came into existence. A detailed physical picture where individual stellar populations can be associated with (tagged to) elements of the protocloud is far beyond our current understanding. Important clues have begun to emerge from both the Galaxy (near-field cosmology) and the high redshift universe (far-field cosmology). Here we focus on the fossil evidence provided by the Galaxy. Detailed studies of the Galaxy lie at the core of understanding the complex processes involved in baryon dissipation. This is a necessary first step toward achieving a successful theory of galaxy formation.

Astronomical Institute of the University of Basel (Switzerland). Meeting hosted by **Eva Grebel**.

Bird watching – Canberra (2014)

Subaru PFS survey

- Wide-field (1.3 degrees) — massively-multiplexed (2394 fibers) — wide wavelength coverage (0.38 - 1.26 μm) via three-armed spectrographs at medium-low resolution modes.
- 360 nights survey undertaken in 6 years time (starting ~Feb 2024).
- 3 major Science topics: **Cosmology, Galactic Archaeology & Galaxy evolution.**

Fundamental questions in the dark sector with significan implications for Cosmology, galaxy evolution and the origin of the Milky Way Galaxy.

The people behind the scenes

Principal Investigator: **Hitoshi Muryama**
Project Manager: **Naoyuki Tamura**

Galactic Archaeology Working Group Chairs:
Rosemary Wyse
Masashi Chiba
Evan Kirby

Galactic Archaeology Team:
Ana Chies Santos, Anna Sajina, Brent Belland, Carrie Filion, Borja Anguiano, Chiaki Kobayashi, Daichi Kashino, Elisa Ferreira, Tilman Hartwig, Ivanna Escala, Kohei Hayashi, Alex Szalay, Laszlo Dobos, Maximilian Fabricius, Miho N. Ishigaki, Mirko Simunovic, Mohammad Mardini, Nicole Louise Miranda, Qianfan Xing, Robert Lupton, Tamas Budavari, Vincent Le Brun, Viska Wei, Ying Zu, Yutaka Hirai

Collaboration of PFS

The Subaru Prime Focus Spectrograph (PFS) Collaboration Institutes

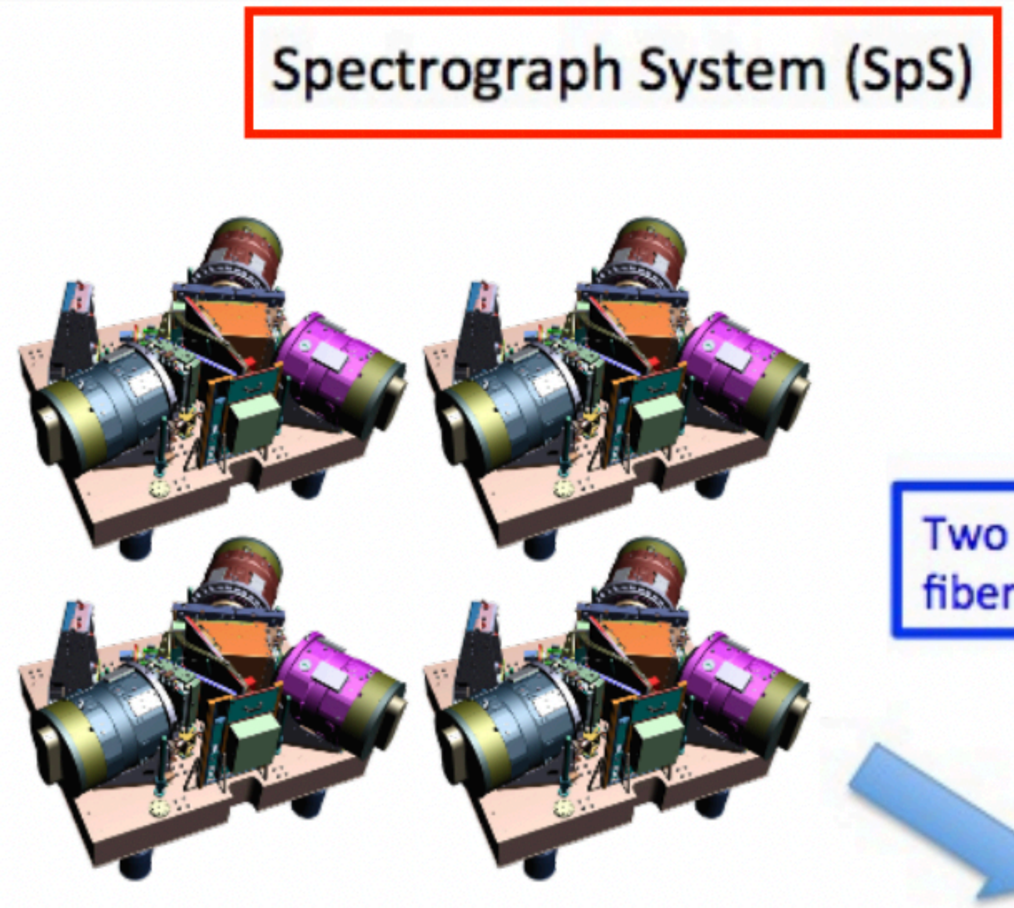
The surveys landscape (2024 - onwards)

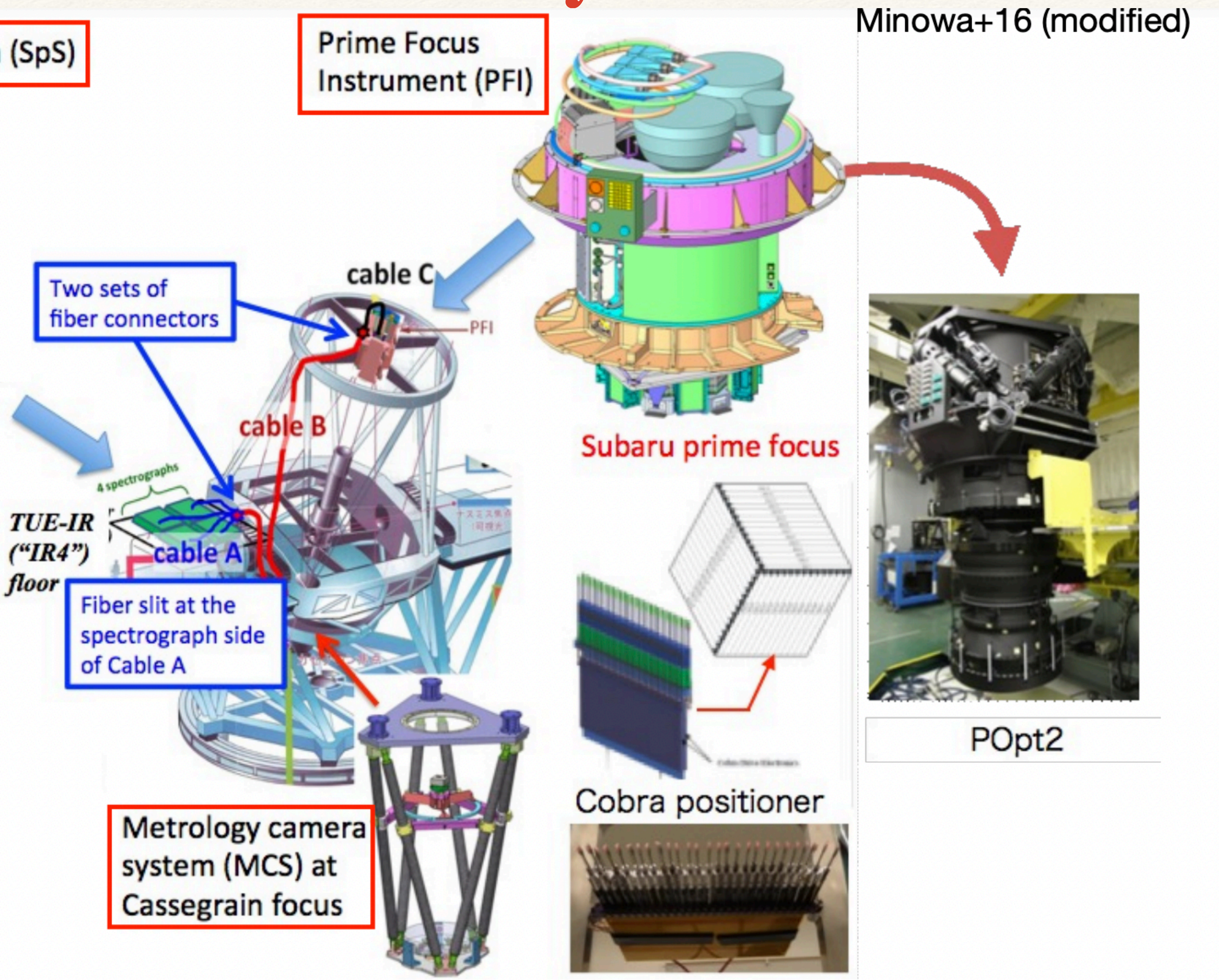
Table 1. Contemporary Multiplexed Spectrographs

Instrument	Hemisphere	Mirror Meters	Fibers	Field of View (sq deg)	Wavelength Nanometers	Resolution	Limiting Magnitude
PFS	Northern	8.2	2394	~ 1.25	Blue: 380 - 650	$\sim 2,300$	$g \sim 23$
					Red (Low-Res): 630 - 970	$\sim 3,000$	
					Red (Med-Res): 710 - 885	$\sim 5,000$	$g \sim 23$
					Infrared: 940 - 1260	$\sim 4,300$	
MOONS	Southern	8.2	1000	~ 0.14	RI (Med-Res): 647 - 955	$\sim 4,100$	mag(AB) ~ 23
					YJ (Med-Res): 934 - 1350	$\sim 4,300$	mag(AB) ~ 23
					H (Med-Res): 1452 - 1800	$\sim 6,600$	mag(AB) ~ 23
					RI (High-Res): 760 - 890	$\sim 9,200$	$RI_{AB} \sim 17.5$
					H (High-Res): 1521 - 1641	$\sim 19,700$	$H_{AB} \sim 17.0$
4MOST	Southern	4.1	2436	~ 4.1	Blue (Low-Res): 370 - 554	~ 5000	mag(AB) ~ 20.2
					Green (Med-Res): 524 - 721	~ 6500	mag(AB) ~ 20.4
					Red (Med-Res): 691 - 950	~ 6500	mag(AB) ~ 20.2
					Blue (High-Res): 392.6 - 435	$\sim 19,5000$	mag(AB) ~ 15.7
					Green (High-Res): 516 - 573	$\sim 19,500$	mag(AB) ~ 15.8
					Red (High-Res): 610 - 679	$\sim 19,500$	mag(AB) ~ 15.8
DESI	Northern	4	5000	~ 8	Blue: 360 - 555	~ 2600	$r \sim 19$
					Red: 555 - 656	$\sim 3,650$	$r \sim 19$
					Infrared: 656 - 980	$\sim 4,600$	$r \sim 19$
WEAVE	Northern	4.2	964/940	~ 3.14	Blue (Med-Res): 366-606	$\sim 5,000$	$V \sim 21$
					Red (Med-Res): 579 - 959	$\sim 5,000$	$V \sim 21$
					Blue (High-Res): 404 - 465	$\sim 20,000$	$G \sim 16$
					Blue (High-Res): 473 - 545	$\sim 20,000$	$G \sim 16$
					Red (High-Res): 595 - 685	$\sim 20,000$	$G \sim 16$
SDSS-V	Northern	2.5	300	~ 7.0	Infrared (High-Res): 1500 - 1700	$\sim 22,500$	$H \sim 13.4$
	Southern	2.5	300	~ 2.8	Infrared (High-Res): 1500 - 1700	$\sim 22,500$	$H \sim 13.4$

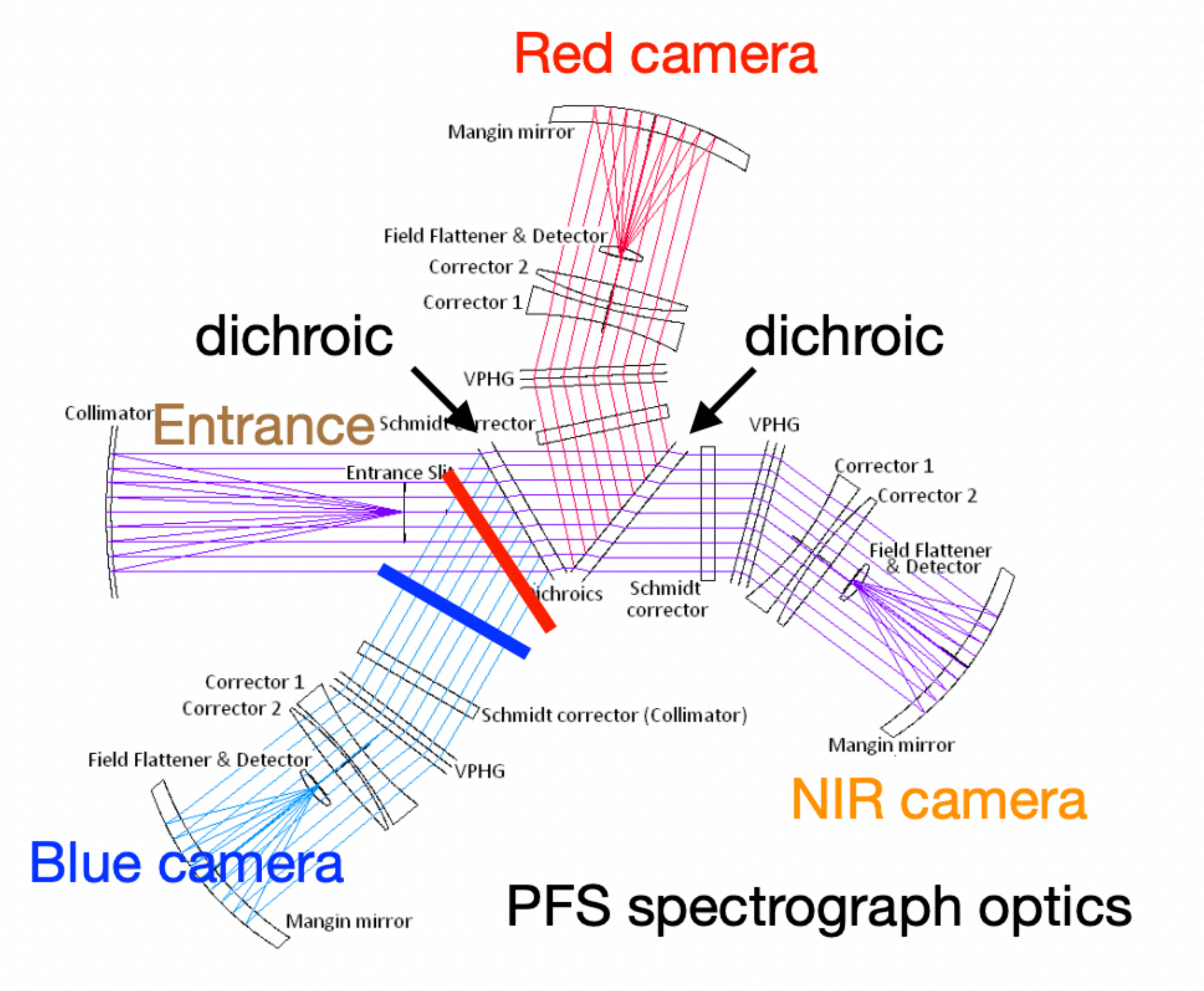
PFS GA White Paper

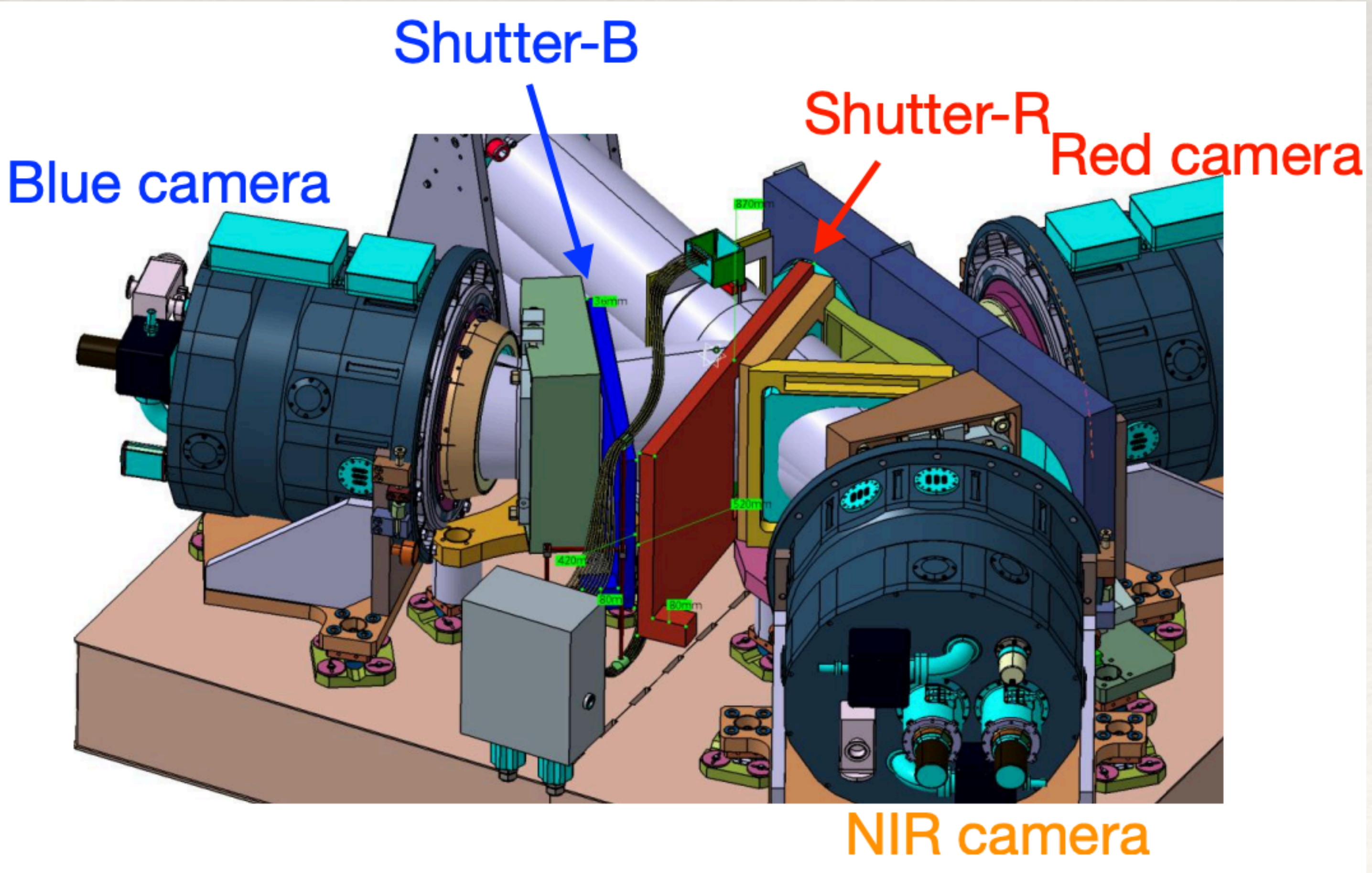
PFS Survey - The instrument





PFS specification:
- ~1.3 deg diameter (hexagonal FoV)
- 2394 science fibers
- Quick fiber configuration by MCS (~60-120 sec.)
- Spectral coverage: 380 nm - 1260 nm with R~2000-4000
- System throughput: ~20-30 %





PFS expected performance (5σ, 1 hour integration):
- Continuum (3 pix binning) : ~22.5 AB (blue), ~22.4 AB (red), ~21.4 AB (NIR)
- Emission line (σ=70 km/s): ~1 x 10^{-17} erg/s/cm^2

PFS software development:
- Instrument Control Software (ICS)
- Exposure Targeting Software (ETS)
- Data Reduction Pipeline (DRP)
- Survey Planning & Tracking (SPT)

PFS Survey - The science

Galactic archaeology — M31/M33 system — Dwarf spheroidal galaxies

(Kinematics + Chemistry)

— Determination of the dark-matter density profile in dwarf spheroidal galaxies of a range in stellar mass and star-formation history.

— Comparison of the stellar populations in M31 with those of the Milky Way, through the first large-scale spectroscopic survey of individual stars in our companion large disk galaxy.

— Investigation of the response of the Milky Way to the ongoing (minor) mergers with the Sagittarius dwarf and the LMC.

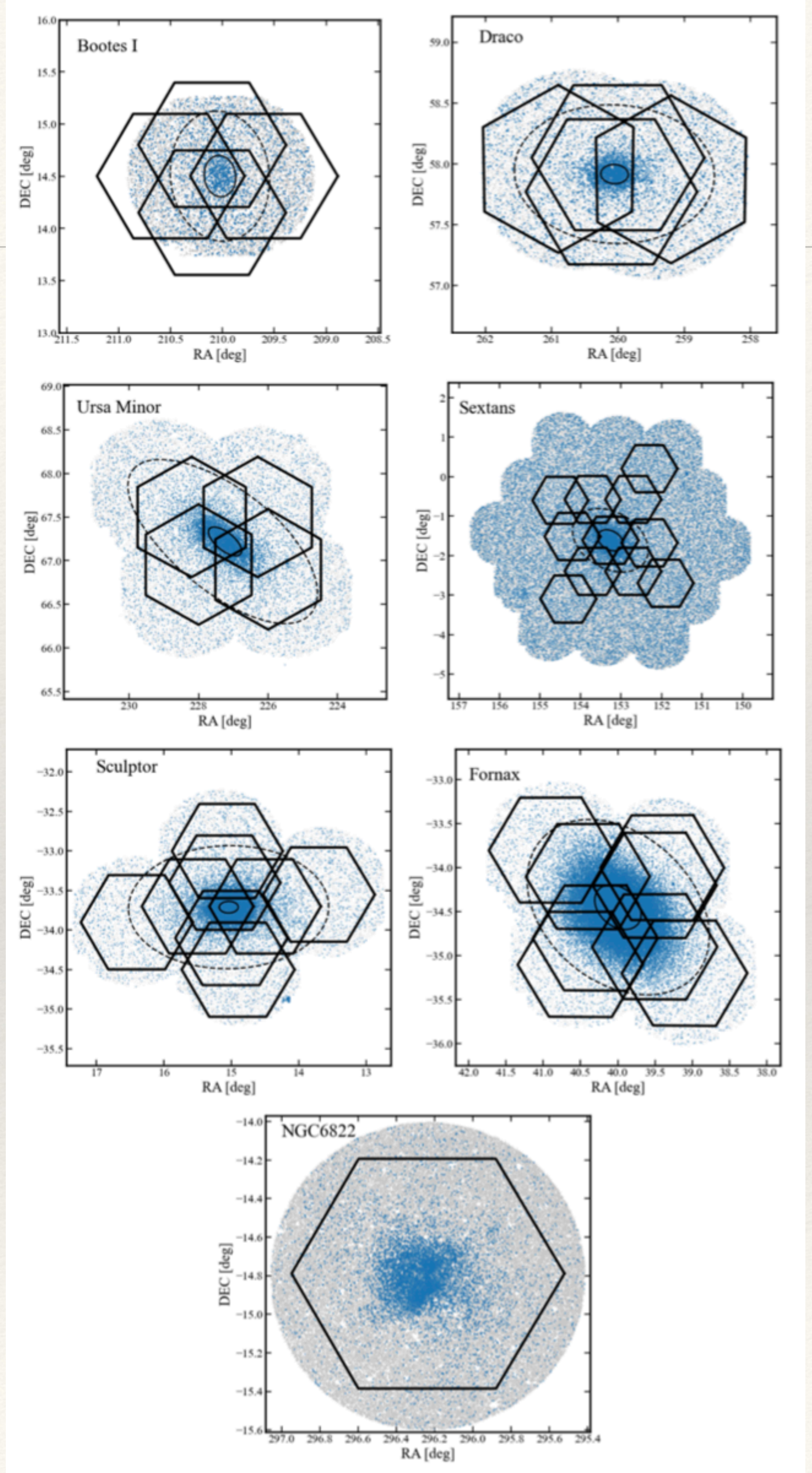
Subaru PFS – dSphs

Table 2. Dwarf Galaxies Targeted by PFS

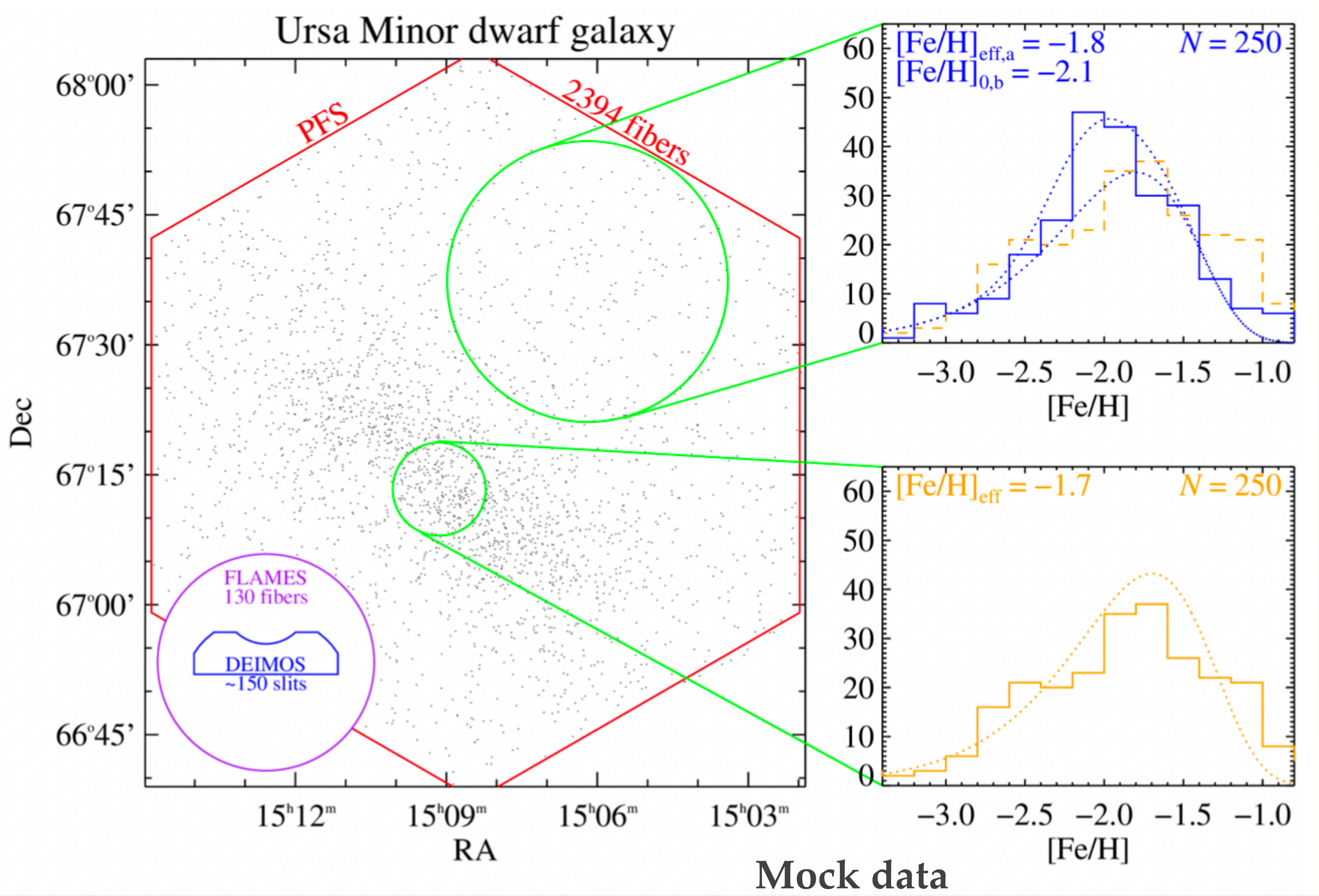
Galaxy	Distance (kpc)	$r_{\rm tidal}$ (′)	M_* ($10^6\ M_\odot$)	⟨[Fe/H]⟩ (dex)	age	$N_{\rm now}$	$N_{\rm pointings}$	$N_{\rm PFS}$
Boötes I	66	33	0.034	−2.6	ancient	118 (63)	4	2000
Draco	76	42	0.32	−1.9	ancient	269 (352)	4	5000
Ursa Minor	76	51	0.54	−2.1	ancient	190 (226)	4	6000
Sextans	86	83	0.70	−1.7	ancient	441 (301)	11	6500
Sculptor	86	77	3.9	−1.9	ancient	1497 (608)	8	7000
Fornax	147	71	24	−1.0	moderate	2603 (1700)	8	7500
NGC 6822	460	⋯	83	−1.0	young	299	1	1000

Dark matter content of dwarf galaxies

PFS can provide both the sample sizes and velocity precision required to determine whether the dSphs' density profiles are consistent with ΛCDM or alternative dark-matter models.



Subaru PFS – dSphs



Stellar elemental abundances in dwarf galaxies

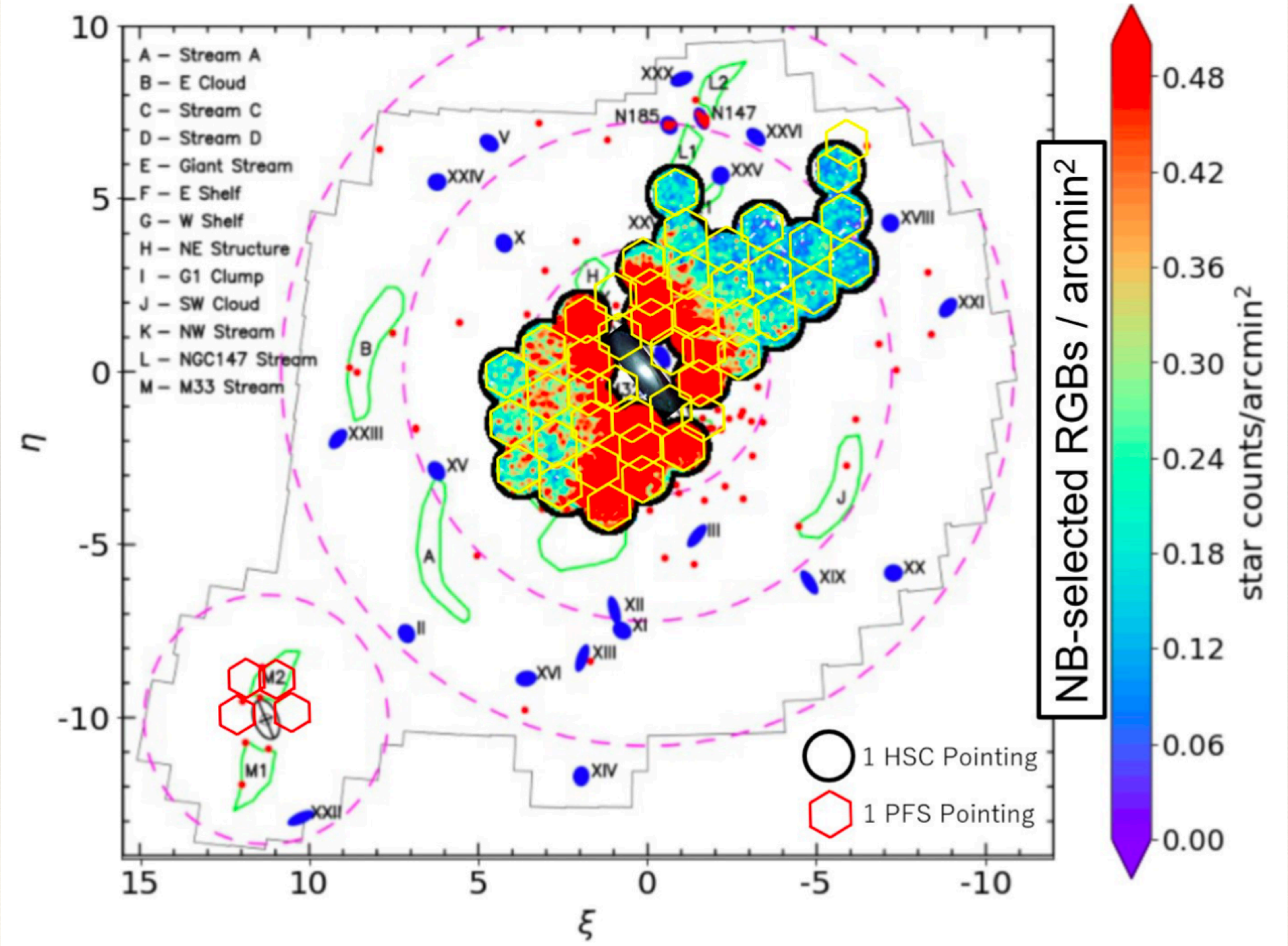
We expect to measure C, Mg, Si, Ca Ti, Cr, Mn, Fe, Co and Ni — validated from low-resolution Keck/DEIMOS spectra (Dugan et al. 2018, Kirby et al. 2018)

In principle, PFS might also be able to measure Na, Al, K, Sc, V, Y, La and Eu

M31-M33 system

Assembly of luminous and dark halos

Large-scale spectroscopic survey of the internal kinematics and chemistry of M31 and M33



Pre-imaging with Hyper Suprime-Cam and sample selection

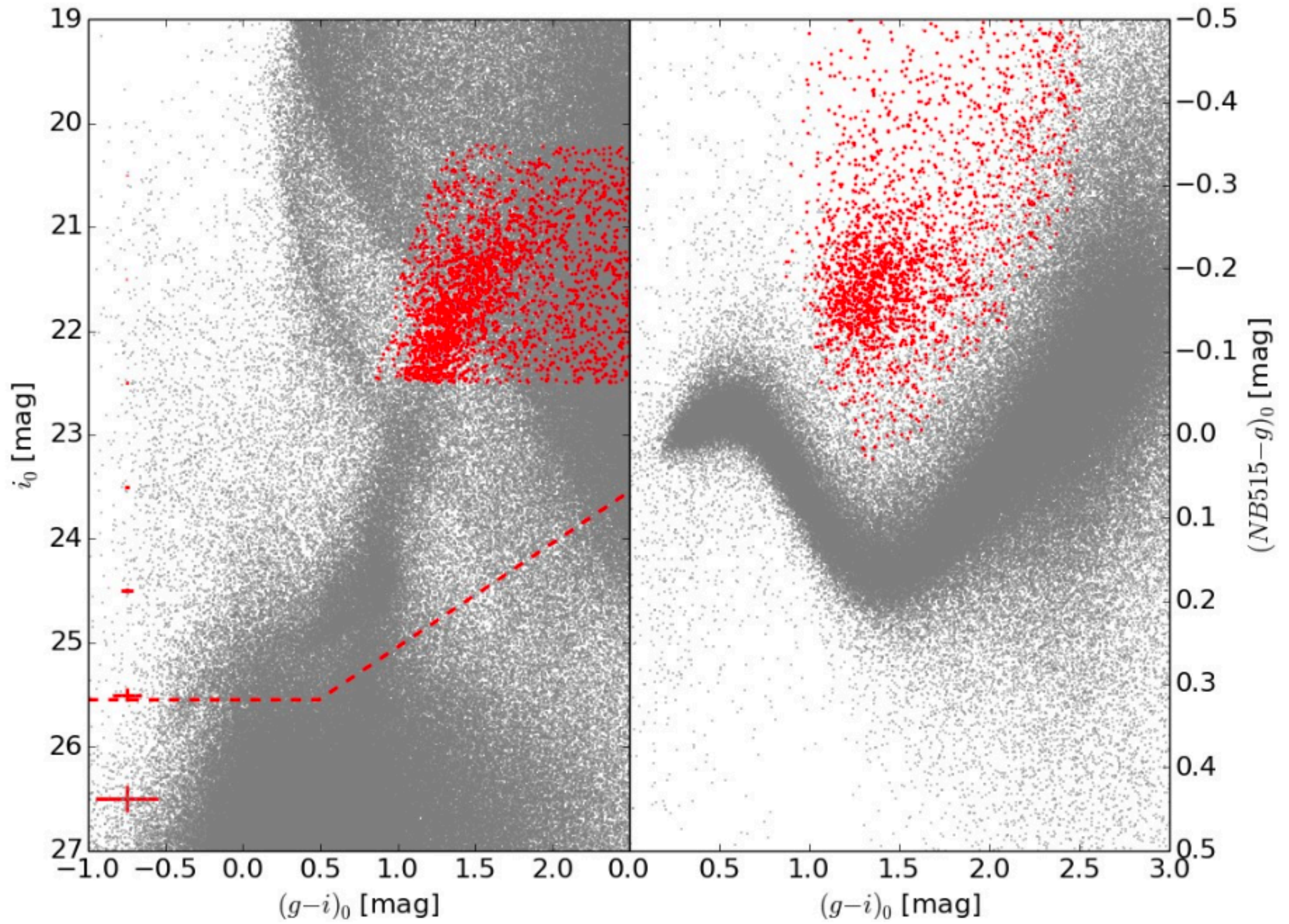
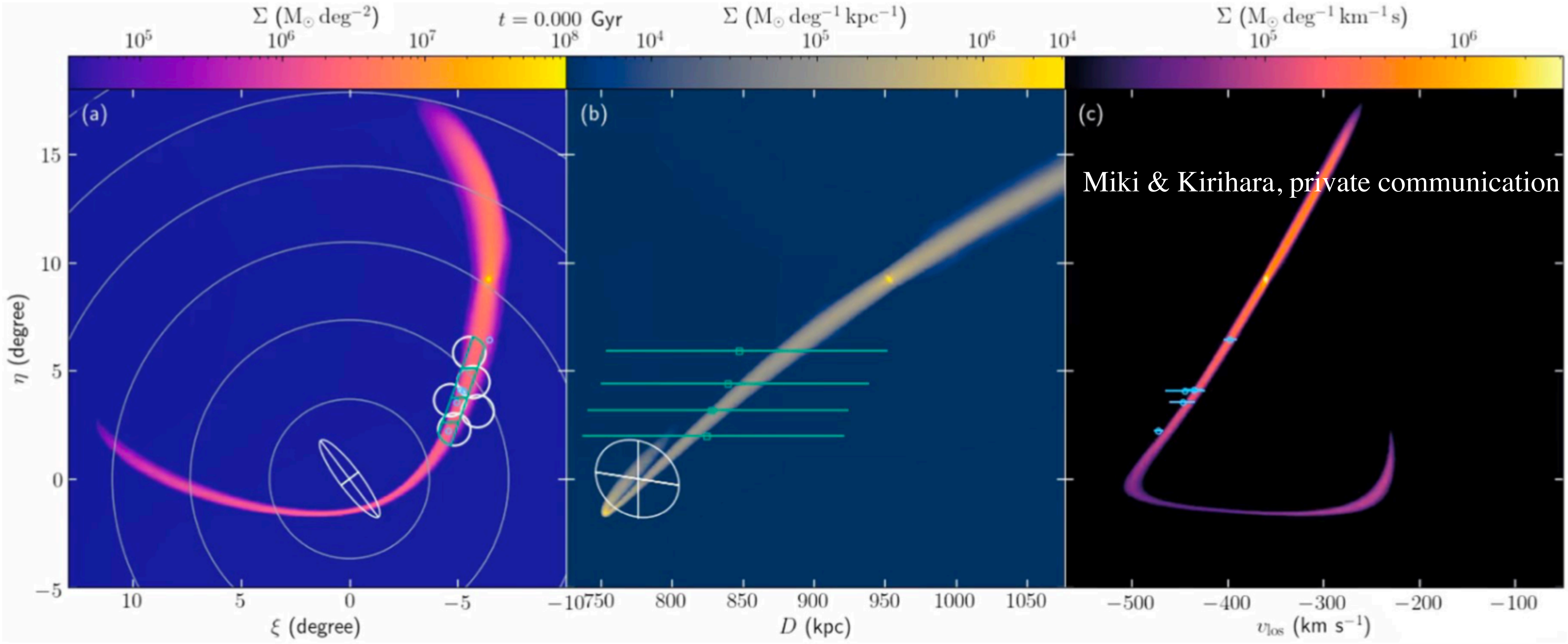


Figure 6. HSC color–magnitude ($(g-i)_0$ vs. i_0) and color–color ($(NB515-g)_0$ vs. $(g-i)_0$) diagrams for stars in M31. Candidate red giant members (*red points*) are identified with this color–color selection and they are also depicted in the left panel.

HSC g- and i-band imagine for large parts of M31 halo (PI: Chiba)

Halo fields using narrow-band filter NB515 helps to distinguish targeted RGB stars in M31 against foreground MW

N-body simulations Northwestern Stream



The Milky Way – The disk in disequilibrium

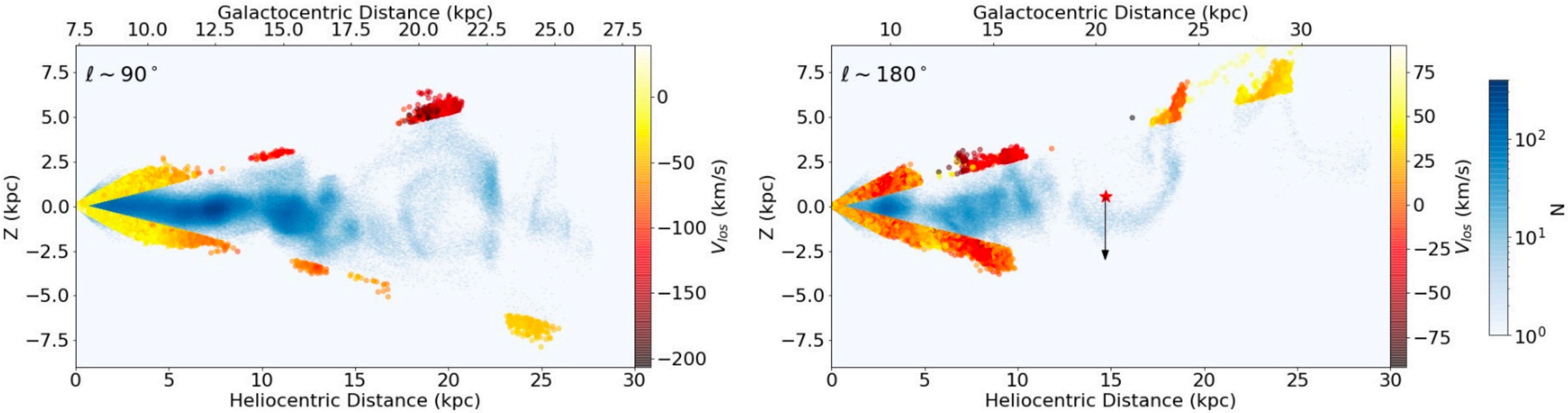


Figure 9. The predicted structure of the outer disk perturbed by a Sgr- like satellite (Hunt et al. 2021). Blue-scale density plots show all of the disk stars that are at longitudes of $\ell \sim 180^\circ$ (right) and $\ell \sim 90^\circ$ (left). Over plotted are the disk stars at the specified longitude at the low-to-intermediate latitudes that PFS will target, color-coded by their line-of-sight velocities. The red star indicates the heliocentric distance and height of the Sgr-like merger at the most recent disk passage about 0.5 Gyr ago, with the arrow indicating the direction of the most recent passage.

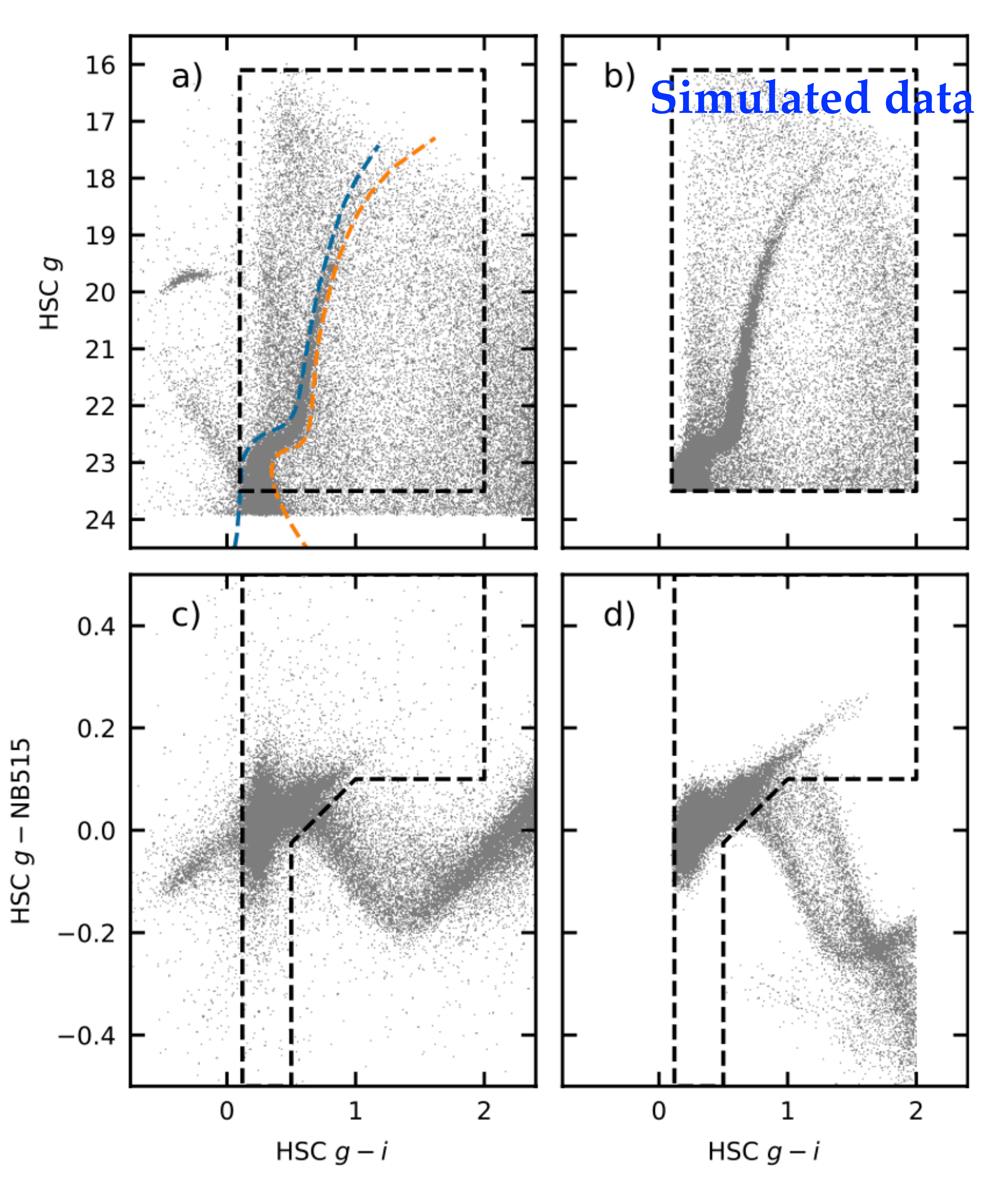
Figure courtesy of Carrie Filion (JHU)

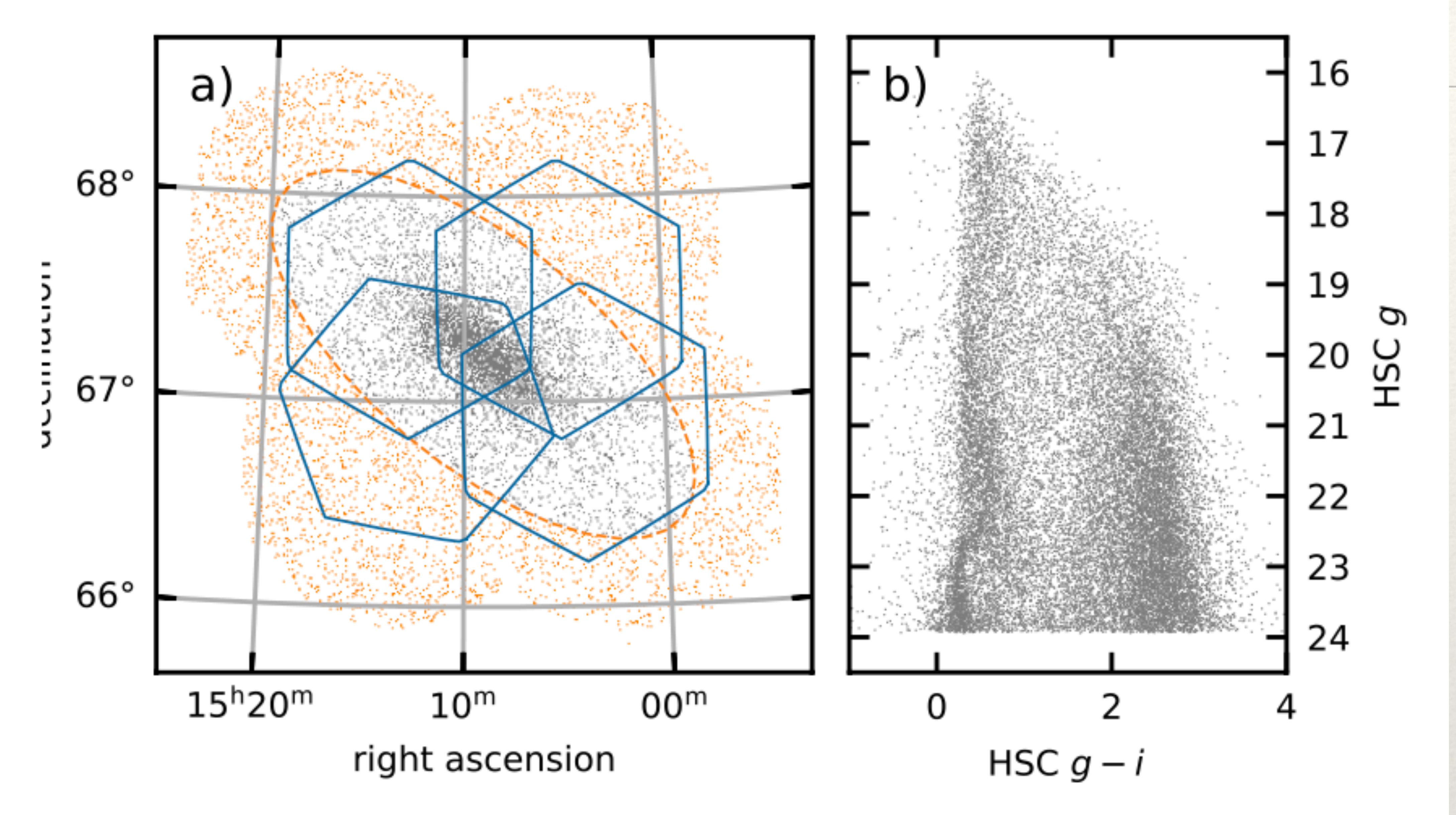
Galactic - Local Group plan

Survey	Mode	Mag. Range (mag)	Exp. (hr)	No. Fields	Survey (nights)	Comments
MW dSph	MR+ LR(blue)	g < 22	3	39 x 2	29.25	Boo I, Fnx, Scl, UMi & Dra, Sextans
MW dIrr	LR	g < 22.5 (i < 21)	5	1 x 2	1.25	NGC6822
MW halo & streams	MR+ LR(blue)	g < 22	3	39	14.6	Halo at b=60, l=90 & 270, 'Field of Streams', cold streams
MW outer disk	MR+ LR(blue)	g < 22	3	44	16.5	Outer disk: l=180
M31 halo	MR	i < 22.3	5	43	26.9	HSC sample
M33 halo	MR	i < 22.3	5	4	2.5	PAndAS & HST image
Total					91	

91 clear nights (=130 x 0.7 weather factor)

Targeting Strategy





Targeting member stars of satellite dwarf spheroidal galaxies will be based on HSC broad band and (when available) narrow band photometry combined with available parallax and proper motion data from *Gaia* DR3, primarily to filter out foreground stars of brighter targets

g-band magnitude limit of $g < 23$.

Figure courtesy of **Laszlo Dobos** (JHU)

Simulated spectra

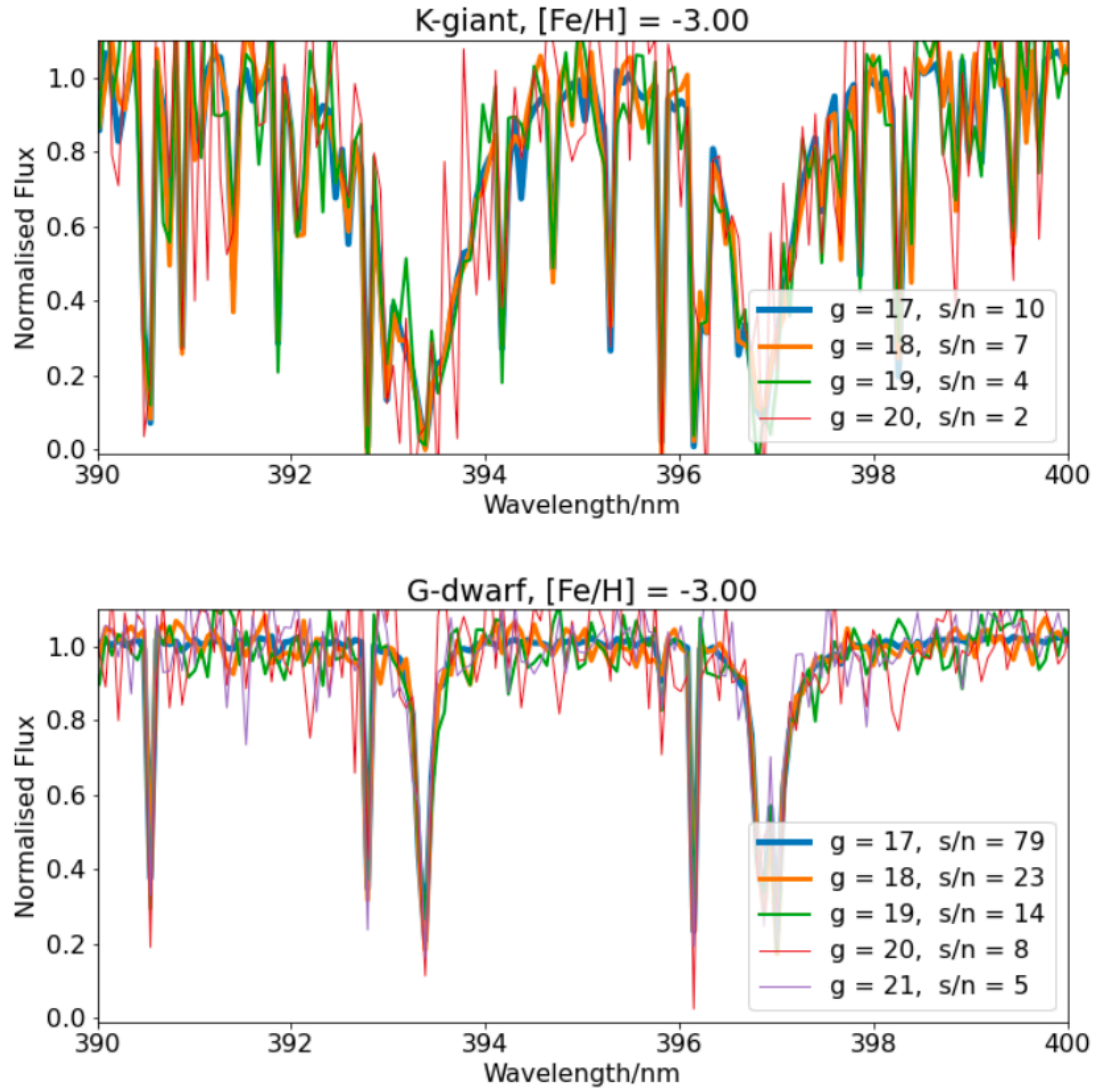
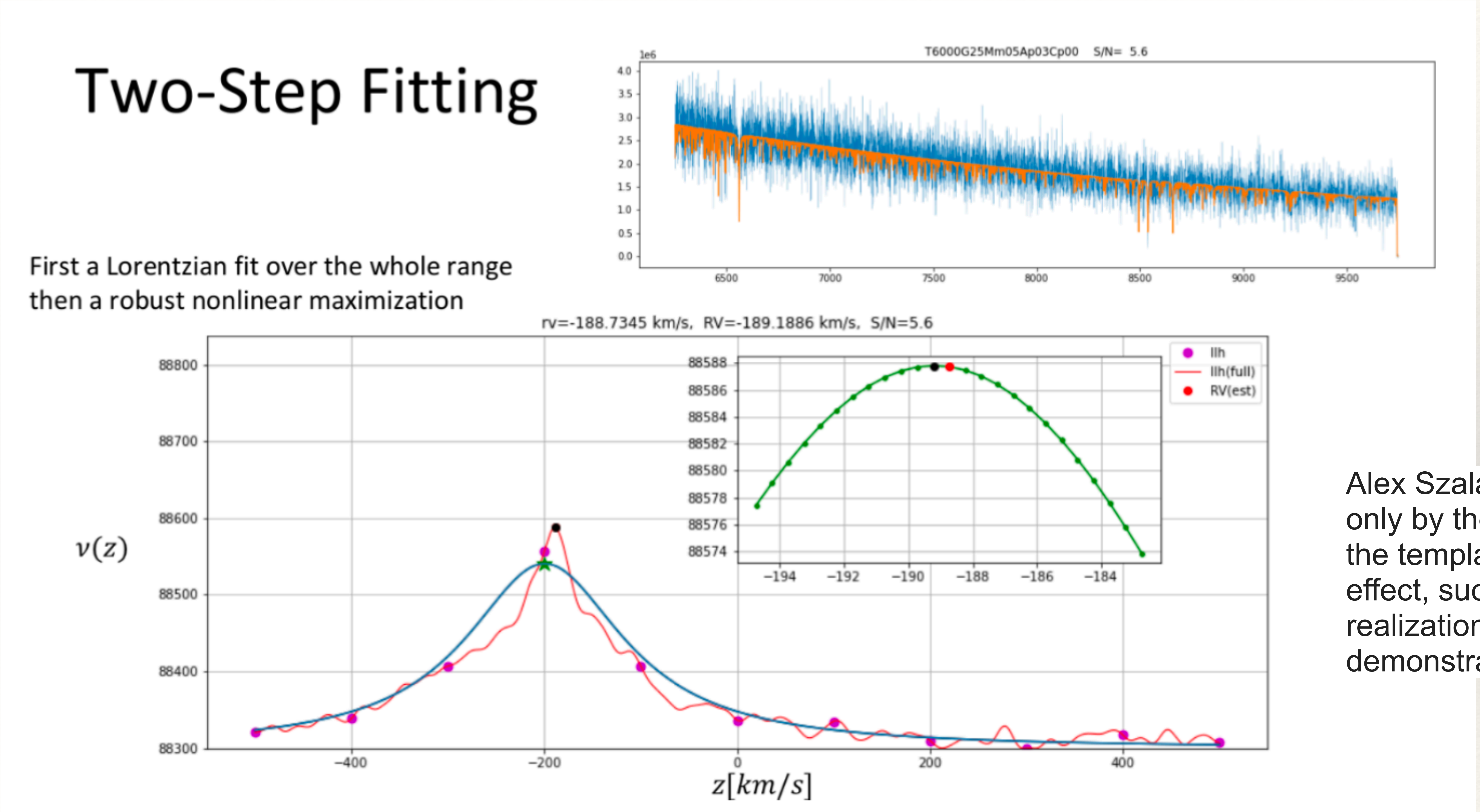


Figure 12. Simulated spectra at 2x15Min exposure time for different magnitudes (coloured lines). The simulations are based on synthetic stellar spectra calculated by Turbospectrum (Plez 2012). The Ca HK doublet is clearly visible down to magnitude 21 for the G-dwarf.

The PFS project has a spectral simulator. **Laszlo Dobos** (JHU) modified this code to run faster and to return a simulated PFS spectrum of a single star of a given Teff, logg, [Fe/H].

Very helpful to evaluate exposure time and S/N for different magnitudes for a range of stellar parameters.

RV methodology



Alex Szalay has written an algorithm that is limited only by the S/N of the spectrum and the accuracy of the template spectra. It is not limited by any other effect, such as rebinning. By simulating multiple noise realizations of the same underlying spectrum, he demonstrated **sub-km/s RV precision.**

Stellar parameters/abundances pipeline

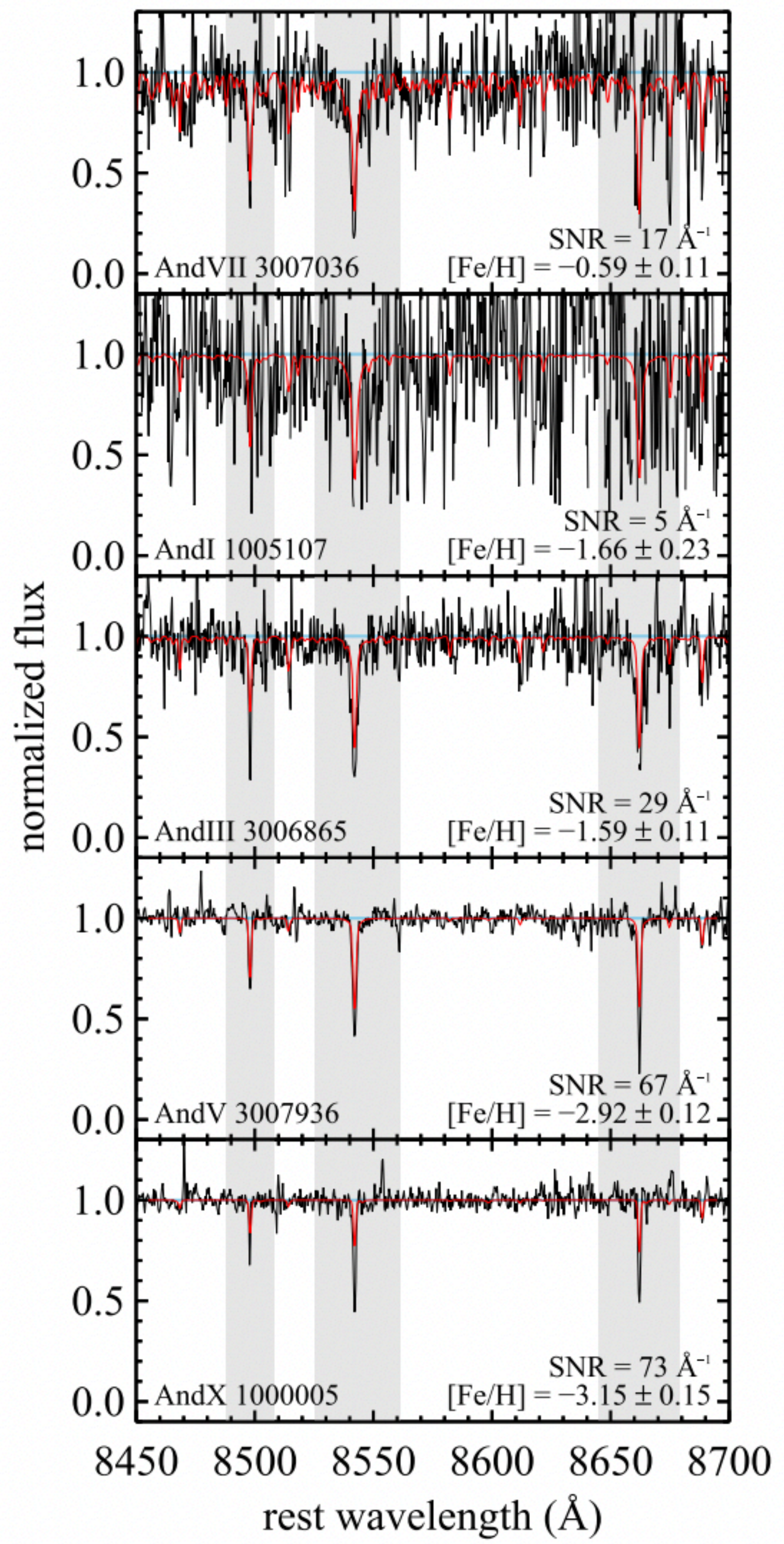


Figure 3. Portions of example DEIMOS spectra in each M31 dSph. The spectra shown are the star with the highest [Fe/H] in And VII, the spectrum in And I with the lowest S/N that still permitted a measurement of [Fe/H], the spectrum in And III with the median S/N, the spectrum in And V with the highest S/N, and the spectrum in And X with the lowest [Fe/H]. The red curve shows the best-fitting synthetic spectrum. The Ca II triplet (gray shading) is not well-modeled, and is excluded from the abundance determination. The full wavelength range is approximately 6300–9100 Å.

drp_ga1d_abund:

- computes photometric values of Teff and logg by assuming an age and matching mag+color with Teff+logg in an isochrone
- continuum-normalizes the input spectrum with a spline
- fits the spectrum to a grid of synthetic spectra with the dimensions Teff, logg,[Fe/H], and [alpha/Fe]. Teff and/or logg can be tied (strictly or loosely) to the photometric values, but they can also be free parameters
- re-determines the continuum by dividing the observed spectrum by the best-fit synthetic spectrum, then fits a spline to the residual
- iterates the fitting until the numbers change by less than some threshold
- returns the fit values of Teff, logg, [Fe/H], and [alpha/Fe]

The code requires a library of synthetic spectra. Currently, the code is set up to use the synthetic spectra computed by Kirby (630-910 nm) and by Escala (410-630 nm) with ATLAS9+MOOG. The code has been tested on a small number of mock spectra.

Kirby et al. 2010, 2020 — Escala et al. 2021

Thank you & Happy Birthday Ken!

Subaru PFS - GA white paper

Draft version September 17, 2022
Typeset using LaTeX **twocolumn** style in AASTeX63

Galactic Archaeology with the Subaru Prime Focus Spectrograph

The Subaru Prime Focus Spectrograph (PFS) Collaboration[1]

[1] *Author list TBD*

ABSTRACT

Let's not forget to edit the abstract! Currently I think it is the SSP abstract. We propose a large-scale survey with PFS to address fundamental and important questions in the dark sector (dark matter and dark energy) with significant implications for cosmology, galaxy evolution and the origin of the Milky Way Galaxy. The unique wide-field and massively-multiplexed spectroscopic capability of PFS will maintain and strengthen Subaru's world-leading role in cosmology and astronomy for the next decade. Our experienced team of astronomers from Japan and the international community has developed an ambitious 360 night survey to be undertaken over 5 years which fully exploits the unique capabilities of PFS to address outstanding questions relating to the history and fate of the Universe as well as the physical processes and role of dark matter in governing the assembly of galaxies including our Milky Way. We commit to fully reducing the data from this landmark survey and making it available to the global astronomical community in a timely manner.

Keywords: Best proposal ever

1. PRIMARY GOALS OF THE PFS GALACTIC ARCHAEOLOGY PROGRAM

Much of the physics of dark matter is manifest on the scales probed by individual galaxies (e.g. Ostriker & Steinhardt 2003). This has the consequence that different types of dark matter make different predictions for observationally accessible properties of the stellar populations within Milky Way-mass (and below) dark-matter

is not used in the other aspects of the overall science case. also where do we discuss photometric temp priors?

1.1. *PFS in Context*

Within this decade, a number of massively multiplexed spectrographs will come online, ushering in a new era of Galactic Archaeology. Many of the surveys to be carried out using these spec-