Towards precise calibrations of wide-field surveys in the era of LAMOST and Gaia

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Significance of calibrations

"Without measurement, there would be no science." — Mendeleev

"You understand something truly only when you can measure it precisely." — Lord Kelvin

Error = random error + systematic/calibration error

Random error = f(SNR)

Outline

- Photometric calibration of imaging surveys
- Wavelength calibration of (slit-less) spectroscopic surveys
- Flux calibration of slit-less spectroscopic surveys
- Summary

Photometric calibration of imaging surveys

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Photometric calibration methods for wide-field photometric surveys

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Abstract

Uniform and accurate photometric calibration plays an important role in the current and next-generation wide-field imaging surveys. Herein, we review the modern photometric calibration methods, including the classic standard star method, “hardware/observation-driven" methods (such as the Ubercalibration, Hypercalibration, and Forward Global Calibration Methods), and “software/physics-driven" methods (e.g., the Stellar Locus Regression, Stellar Locus, and Stellar Color Regression Methods). Further, we discuss their advantages, limitations, and future developments toward millimagnitude precision calibration.

Keywords Figures

interstellar extinction

flux calibration

stellar parameters

photometric surveys

1 引言

Magnitude

$$m_b = -2.5 \log_{10} \frac{C_b}{C_b^{(0)}}$$

$$C_b = \int \frac{f_\lambda(\lambda)}{(h\,c/\lambda)}\, R_b(\lambda)\, \mathrm{d}\lambda$$

$$C_b^{(0)} = \int \frac{f_\lambda^{(0)}(\lambda)}{(h\,c/\lambda)}\, R_b(\lambda)\, \mathrm{d}\lambda\ ,$$

Photon counts of a target
Photon counts of the standard

$$R_b(\lambda) = R_{\mathrm{atmosphere}}(\lambda)\, R_{\mathrm{optics}}(\lambda)\, R_{\mathrm{filter}}(\lambda)\, R_{\mathrm{detector}}(\lambda)$$

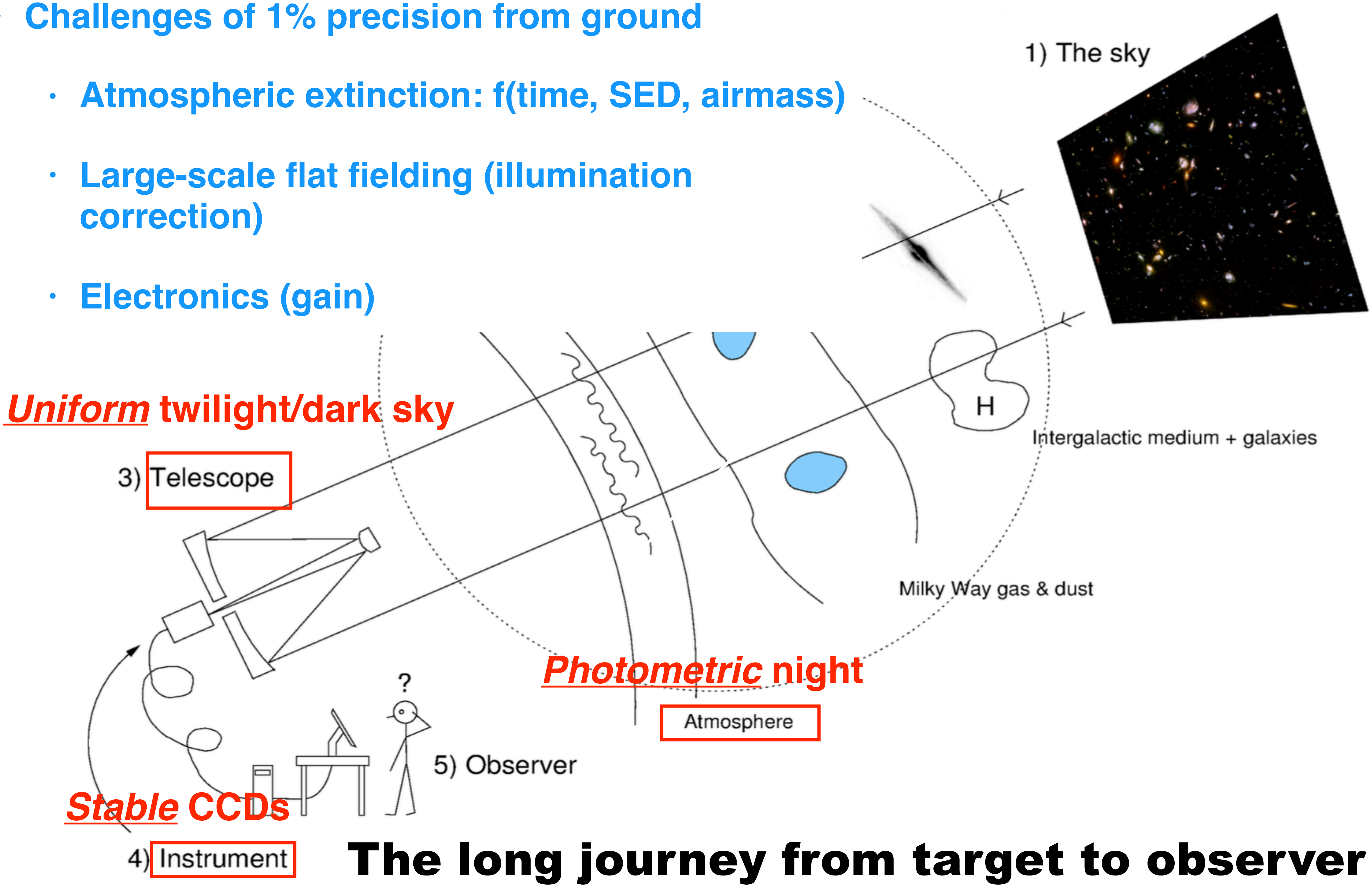
- **Friendly to astronomer: dependent on expected photo counts only, purely observational**
- **Unfriendly to astrophysicist: interpretation involves physical properties of a target ($f_\lambda(\lambda)$) and the measurement effect ($R_b(\lambda)$)**

D. Hogg 2022 (arXiv:2206.00989)

Challenges of photometric calibration

$$R_b(\lambda) = R_{\text{atmosphere}}(\lambda)\, R_{\text{optics}}(\lambda)\, R_{\text{filter}}(\lambda)\, R_{\text{detector}}(\lambda)$$

- Challenges of 1% precision from ground
  - Atmospheric extinction: f(time, SED, airmass)
  - Large-scale flat fielding (illumination correction)
  - Electronics (gain)



The long journey from target to observer

Photometric calibration

- **Absolute calibration vs. Relative calibration**
- **Magnitude calibration vs. Color calibration**
- **mag = mag_raw + zero_point (zpt)**
- **zpt (t) vs. zpt (t,x,y,mag,color)**

Tools of photometric calibration

- Classical standard stars (e.g., Landolt 1992), but too few
- Based on better understanding of astronomical observations
  - (Most) Stars are non-variables (Ubercalibration; Padmanabhan+08);
  - Illumination corrections are uncorrelated between surveys (Hypercalibration; Finkbeiner+15)
  - Forward Global Photometric Calibration (Burke+18)
- Based on better understanding of astronomical objects (stars)
  - Stellar locus is “universal” (stellar locus regression; High+09)
  - Stellar colors are simple (stellar color regression; Yuan+15)

All methods are complementary

Ubercalibration

- require over-lapping observations
- 1-2 % precision in SDSS and 1% precision in PS1

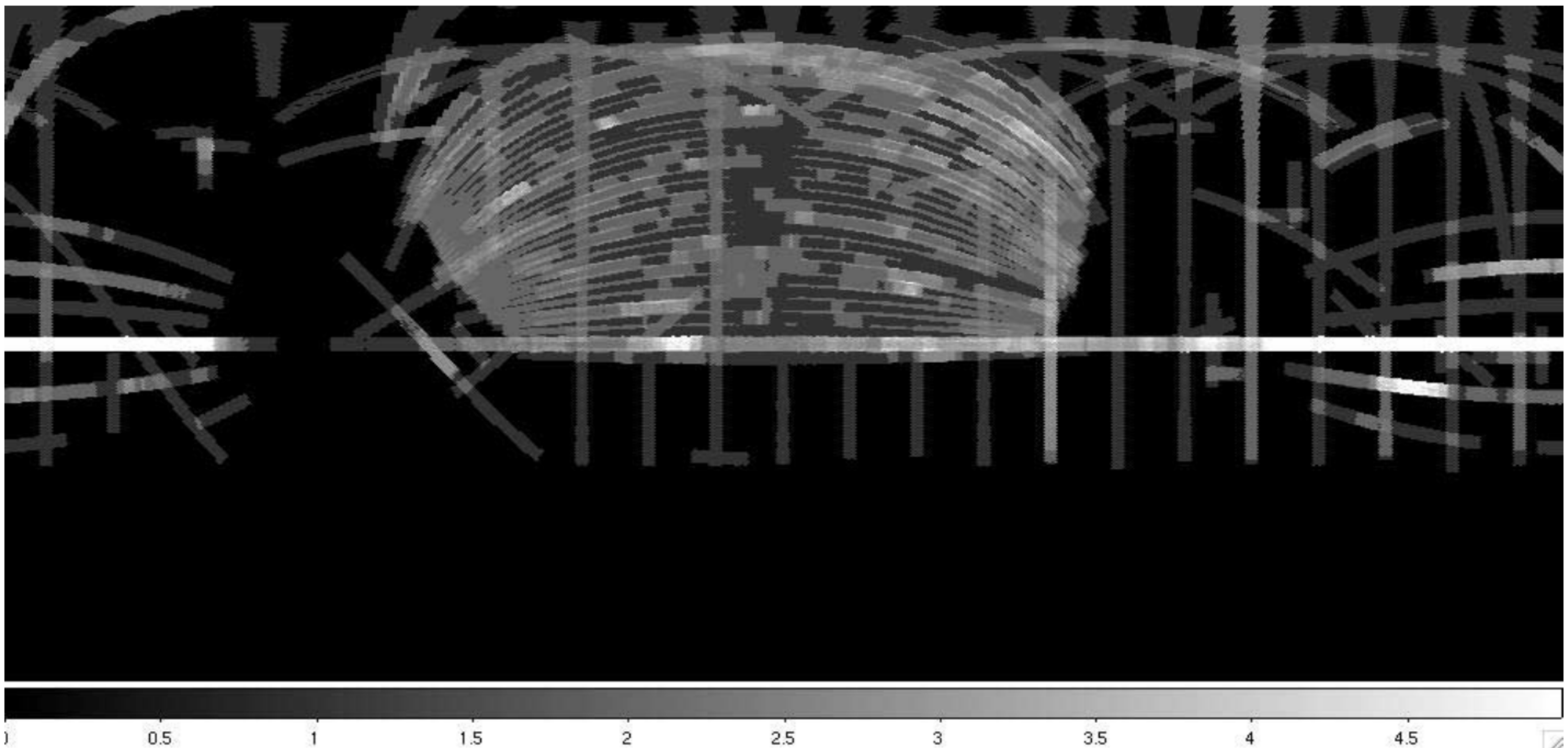


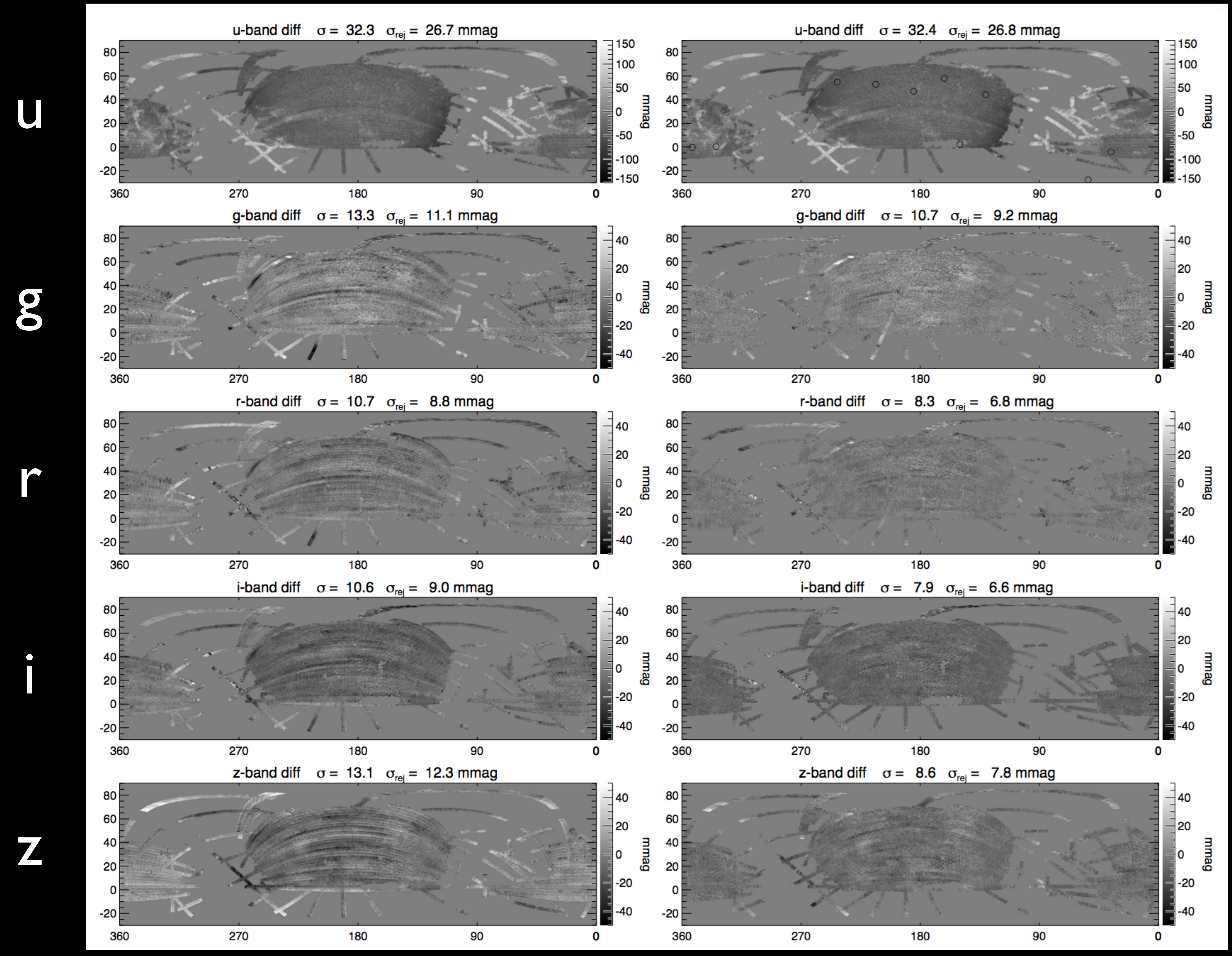
FIG. 2.—Sky coverage of the SDSS data used in this paper, shown in an equal-area resolution 7 HEALPIX/HEALCART (Górski et al. 1999; Finkbeiner 2004) projection. The *x*-scale covers R.A. $= 0^\circ$–360°, while the *y*-axis runs from decl. $= 90^\circ$ to -90°. The gray scale denotes the mean number of observations of a star in a particular pixel. Note that we saturate at five observations, although on the equatorial (white) stripe, there are pixels with a mean number of observations as high as 15. The bulk of the survey data is in the north Galactic cap, the prominent structure in the center of the image. The equatorial stripe, imaged every fall, is the white horizontal stripe halfway in the image. The approximately equally spaced vertical runs are examples of the Apache Wheel data.

SDSS analysis indicates that unmodeled variations in atmospheric extinction dominate residual calibration errors. Simulations with no random fluctuations achieve calibration errors of 0.1%.

Hypercalibration: a PS1-based recalibration of the SDSS

Finkbeiner+2015

Before recalib.: >10mmag After recalib.: <10mmag



Forward Global Photometric Calibration

(Burke+18)

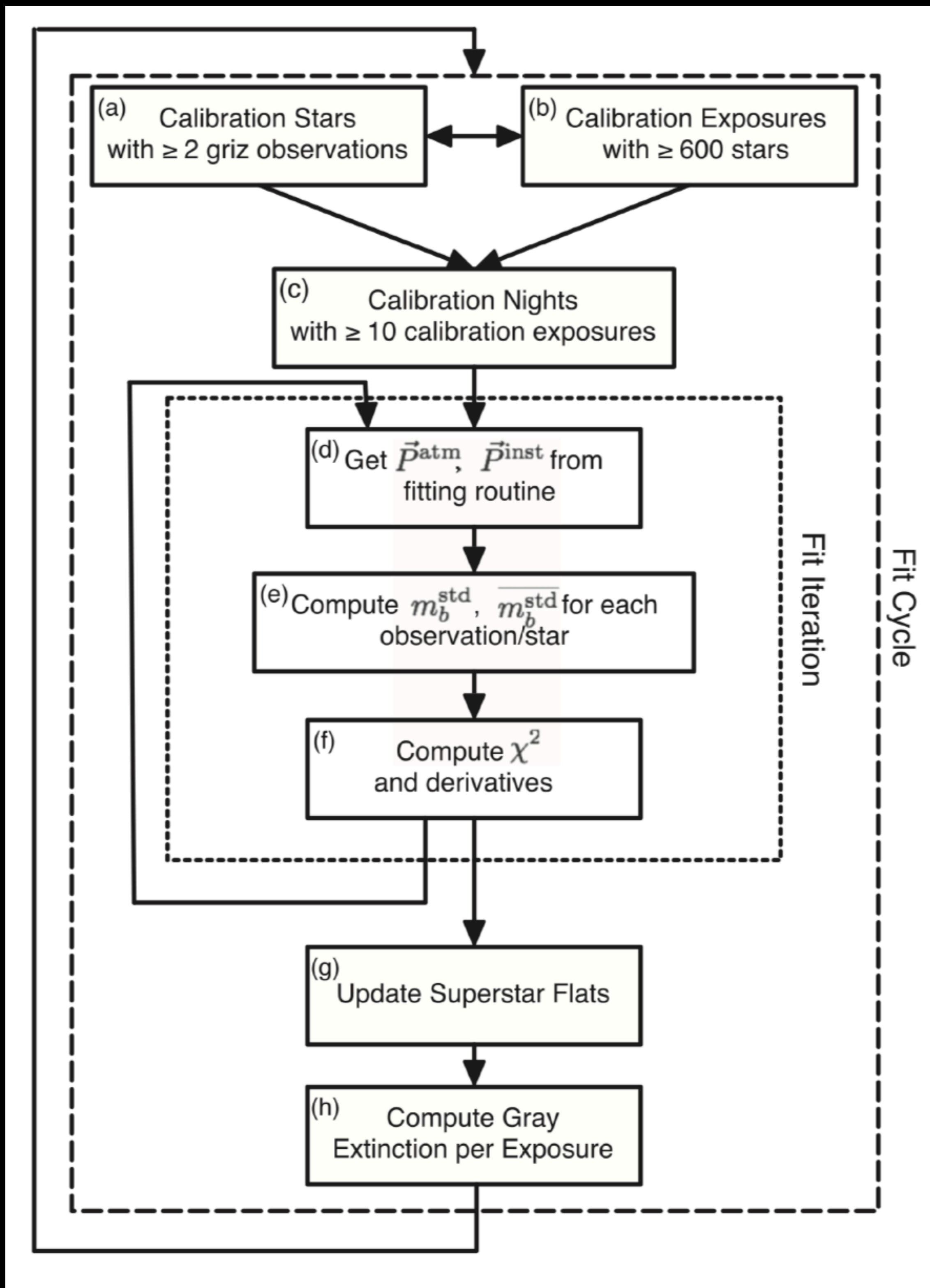


Figure 5. Flowchart of FGCM selection and fit procedure.

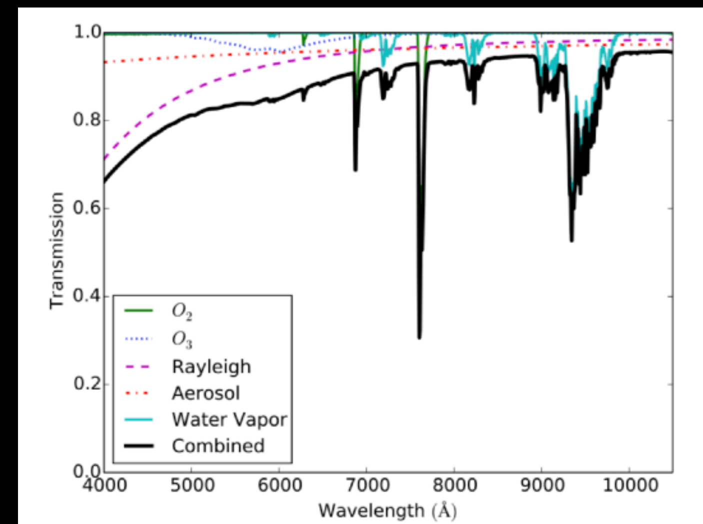


Figure 3. Standard atmosphere for the DES Y3A1 release computed with Gaussian 1 nm FWHM smoothing. The component values are listed in Table 1.

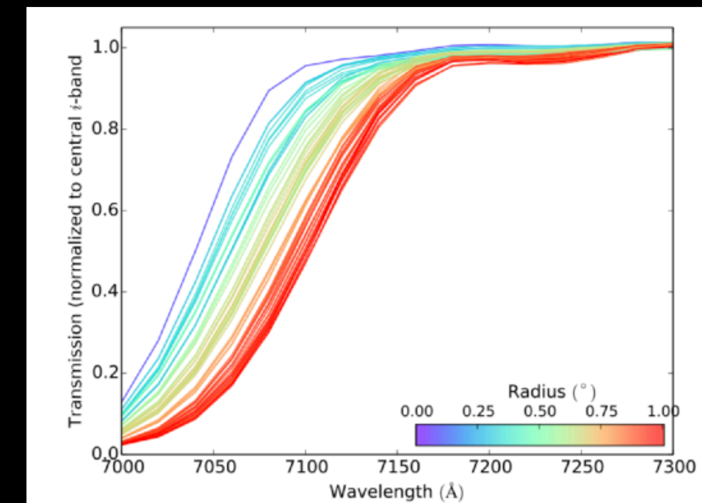


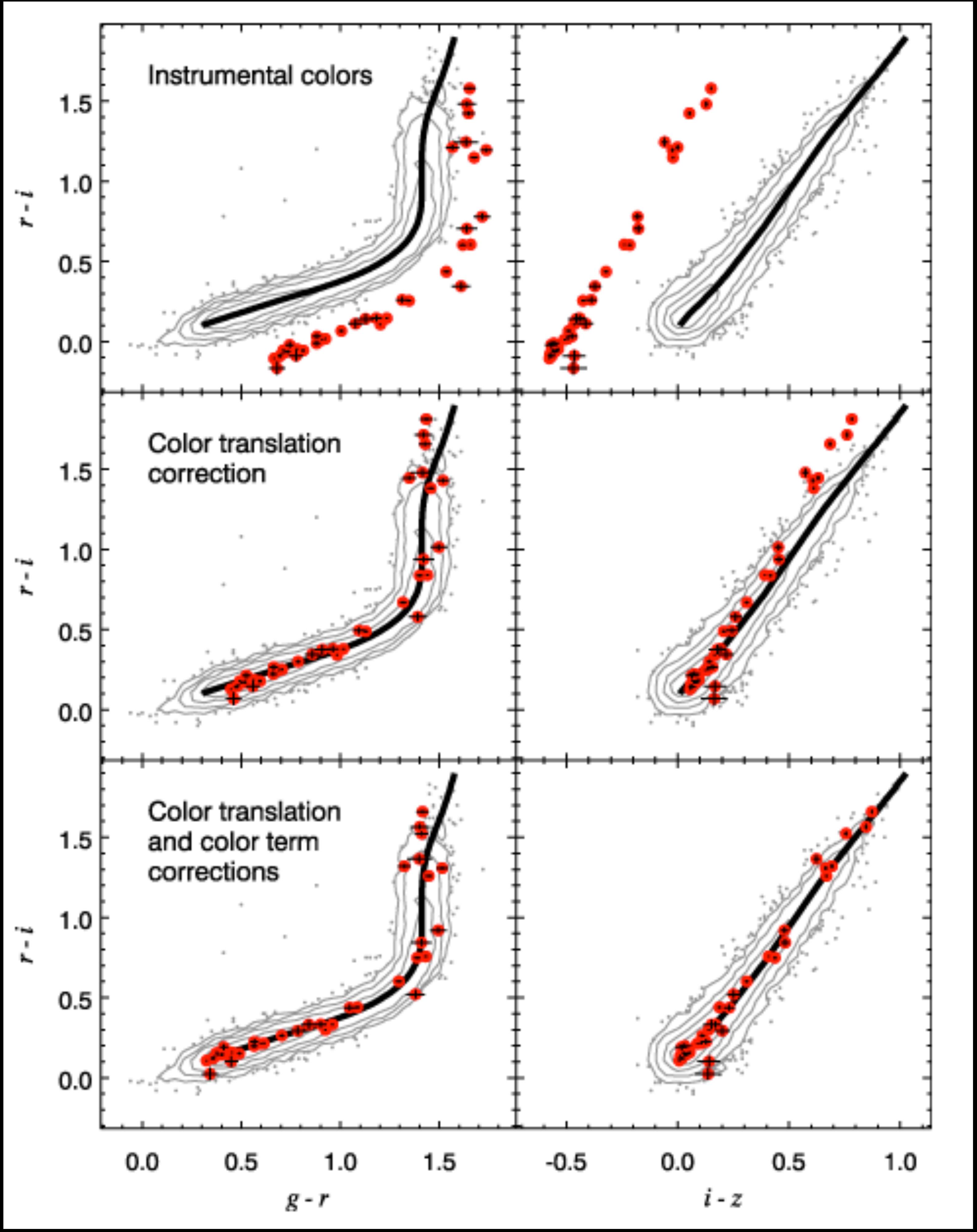
Figure 2. Radial variation of the blue edge of the *i*-band passband due to the filter. Each line represents one CCD, and the color represents the distance (degrees on the sky) of the CCD from the center of the field of view.

Construct **models of atmosphere and instruments**, with parameters constrained by data taken with **auxiliary instrumentation and repeated observations**, with chromatic correction included naturally

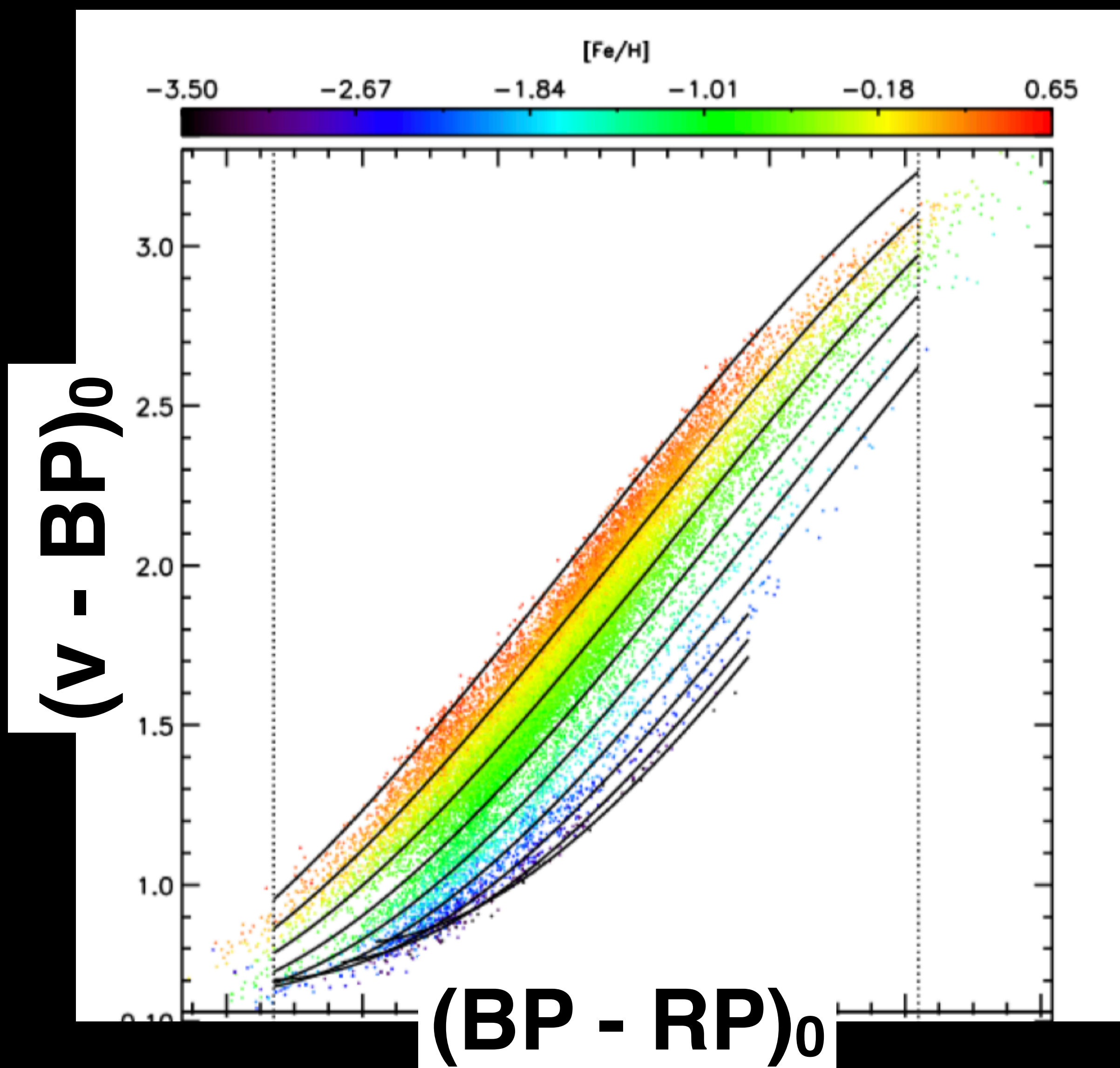
A few mmag precision for DES

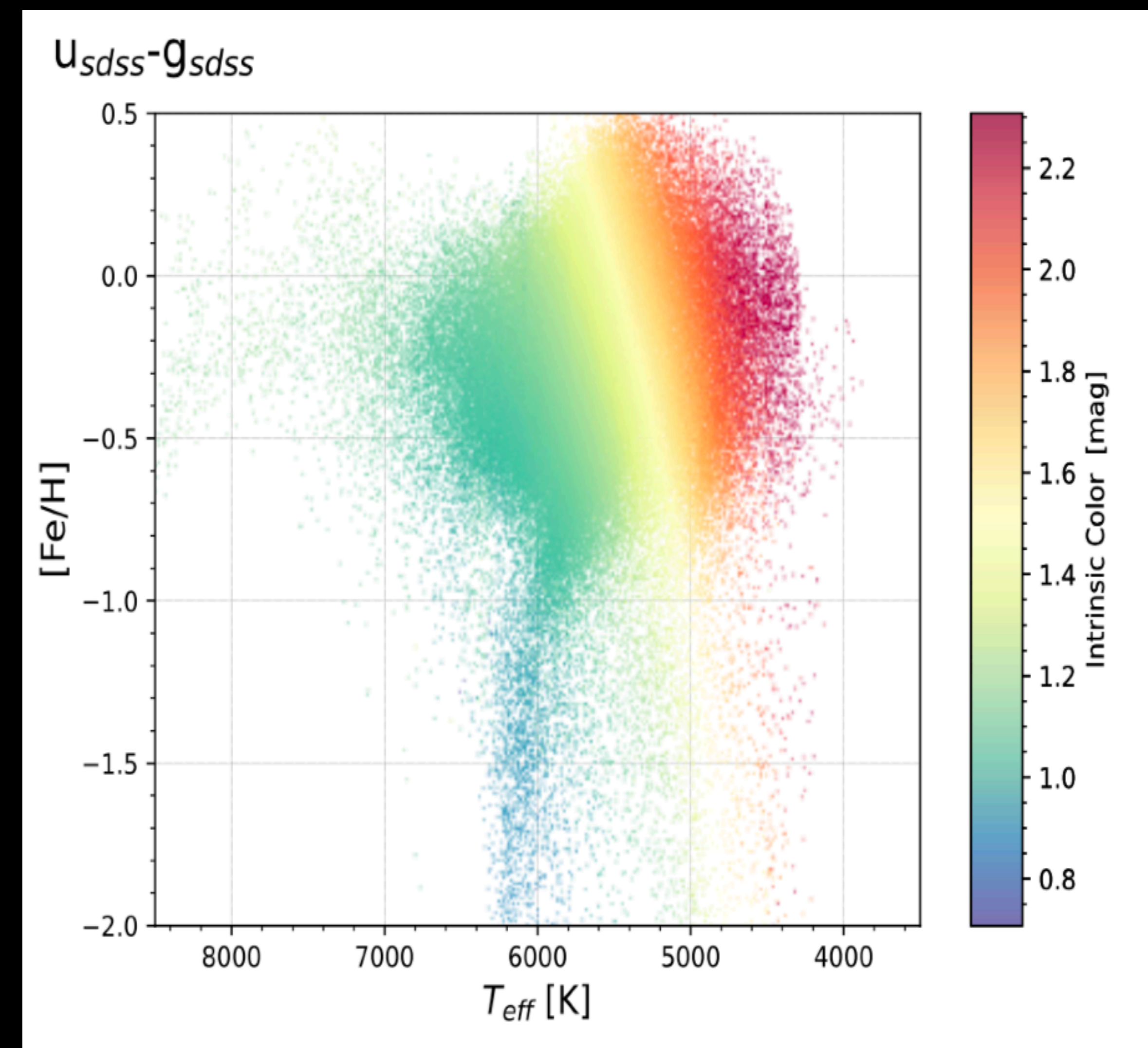
Stellar locus regression (High+09)

- degeneracy problem: require a blue filter (e.g, u-band)
- restricted to low-extinction regions
- a few per cent accuracy



Stellar colors are a little bit complicated

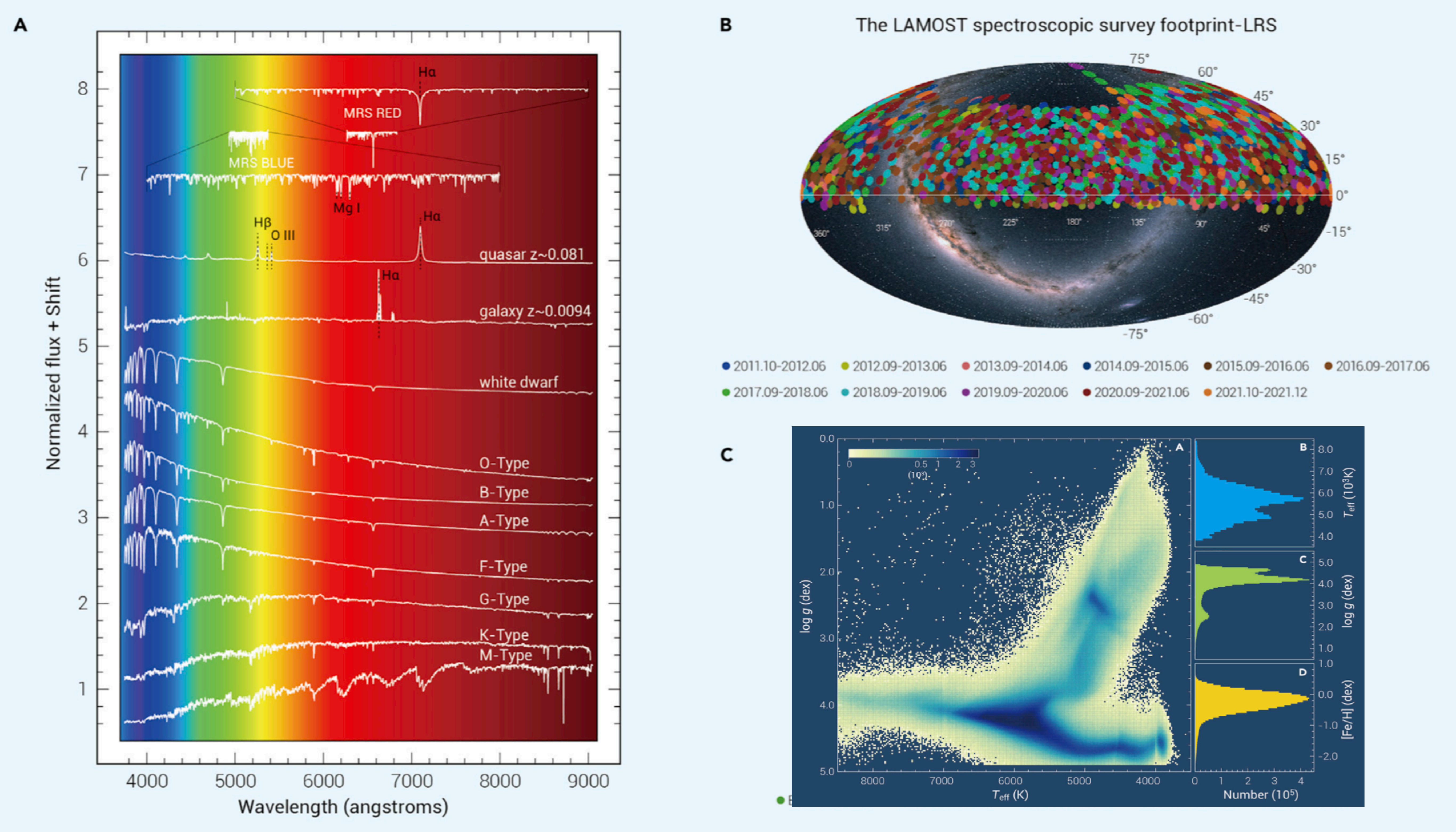




[Fe/H]-dependent stellar locus:
$\text{color1}_0 = f\ (\text{color2}_0, [\text{Fe/H}])$

Star-pair technique:
$\text{color}_0 = f\ (\text{Teff}, [\text{Fe/H}], \text{Logg}, ..)$

LAMOST: delivering ~10^7 stellar spectra/parameters



Yan et al. 2022

Stellar color regression

Yuan et al. 2015
Huang et al. 2022

Stellar colors are (relatively) simple

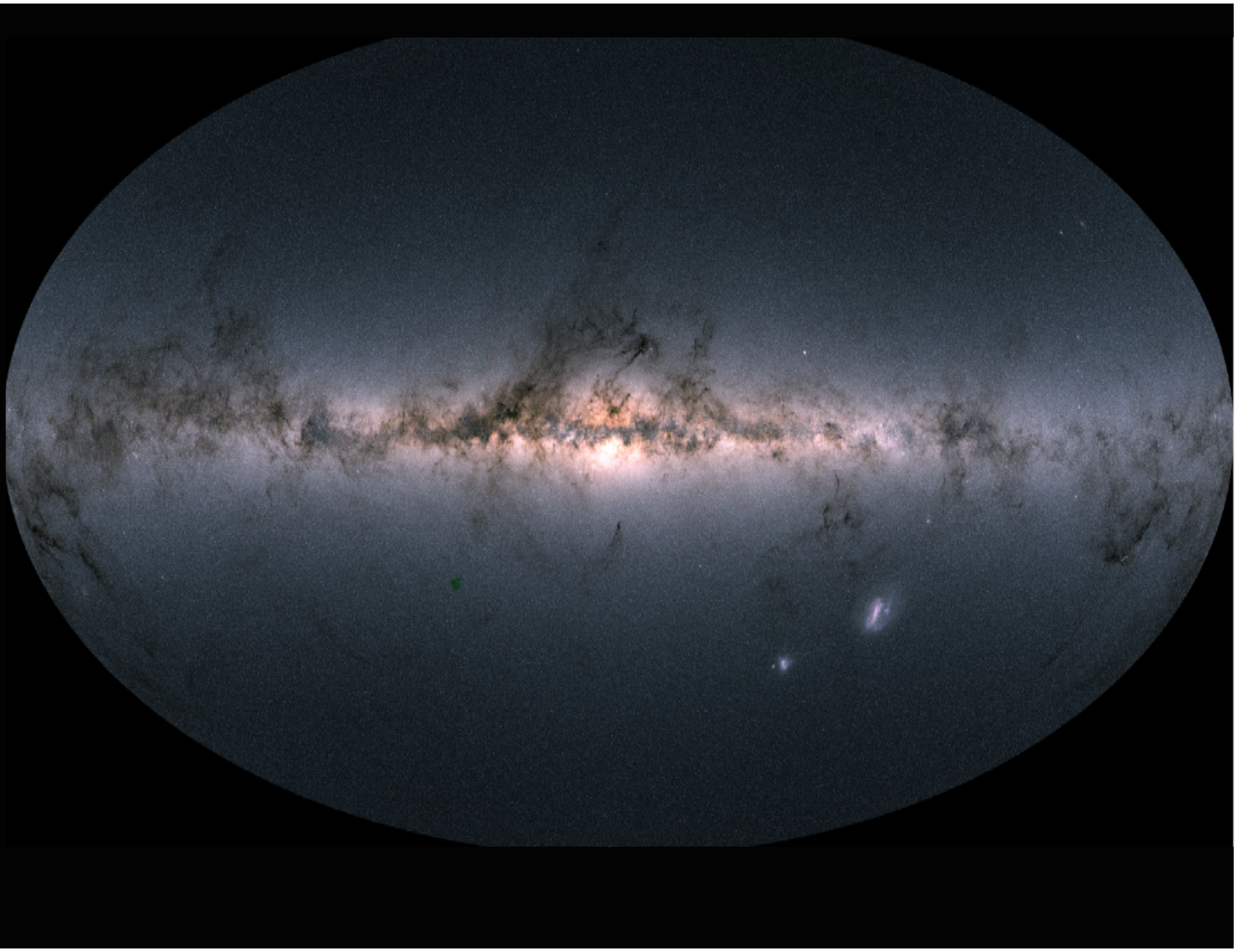
- Color_0 = f (Teff, [Fe/H], logg, …) — Star-pair
  = f (spectra) — Data-driven
  = (color2, [Fe/H]) — Metallicity-dependent stellar locus
  = f (U-B, B-V, V-R, ..) — Data-driven

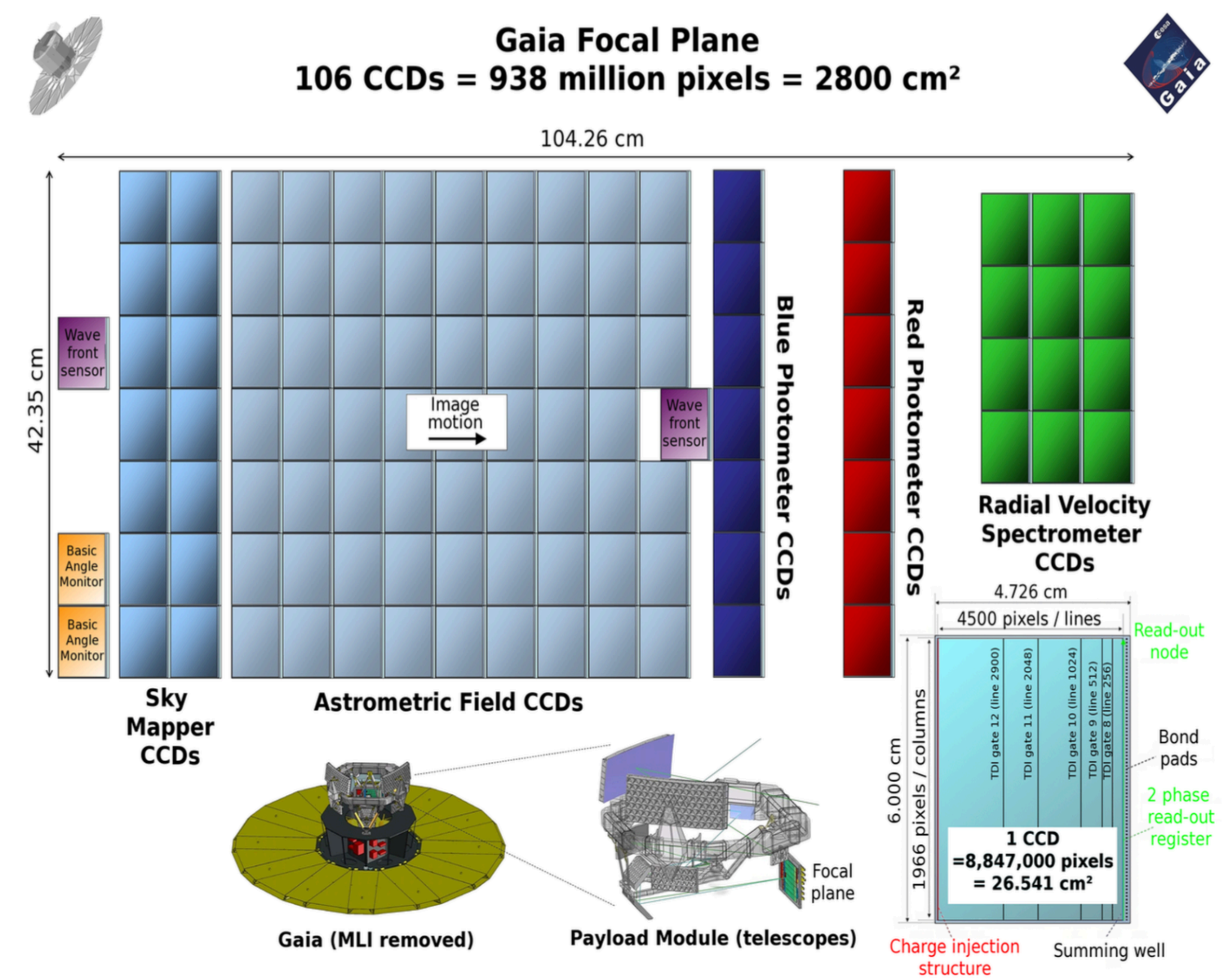
- Color = Color_0 + reddening

Millions of color standard stars in the era of LAMOST …
Millions of standard stars in the era of LAMOST and Gaia

- zero_point = f(frame, X,Y, mag., color, …)

Gaia: delivering mmag precision photometry





1. Space mission → not affected by atmosphere
2. CCD in TDI mode → 1D flat
3. Scanning mode + ~70 visits/5year, → ubercal naturally

SCR in the era of LAMOST and Gaia

Use millions of spectroscopically observed stars as standards

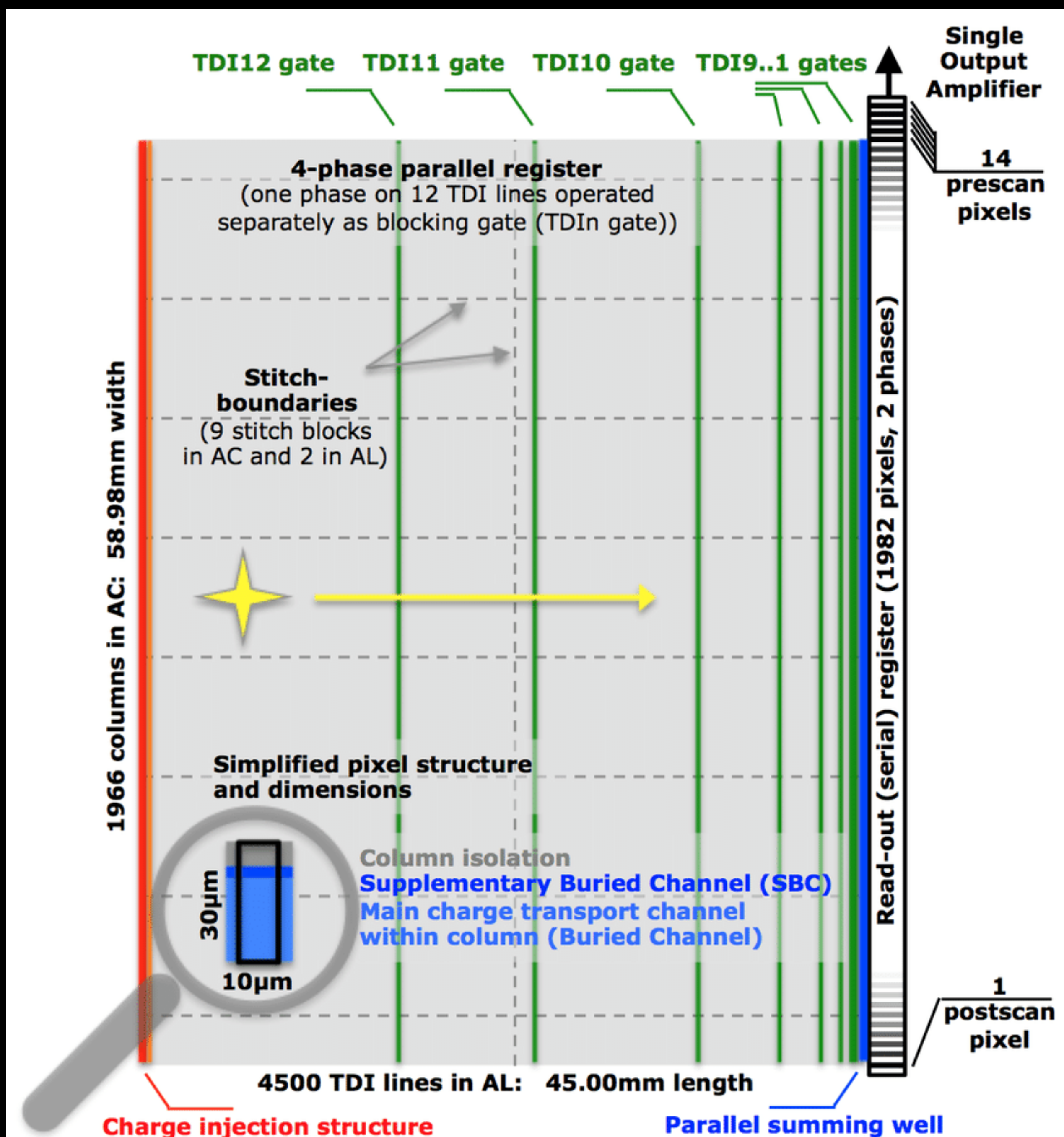
- $G_{BP} - x = (G_{BP} - x)_0$ + k*reddening
- $(G_{BP} - x)_0$ = f(Teff, [Fe/H], logg, a/Fe…)
- x = G_{BP} - f (Teff, [Fe/H], logg, a/Fe) - k*reddening

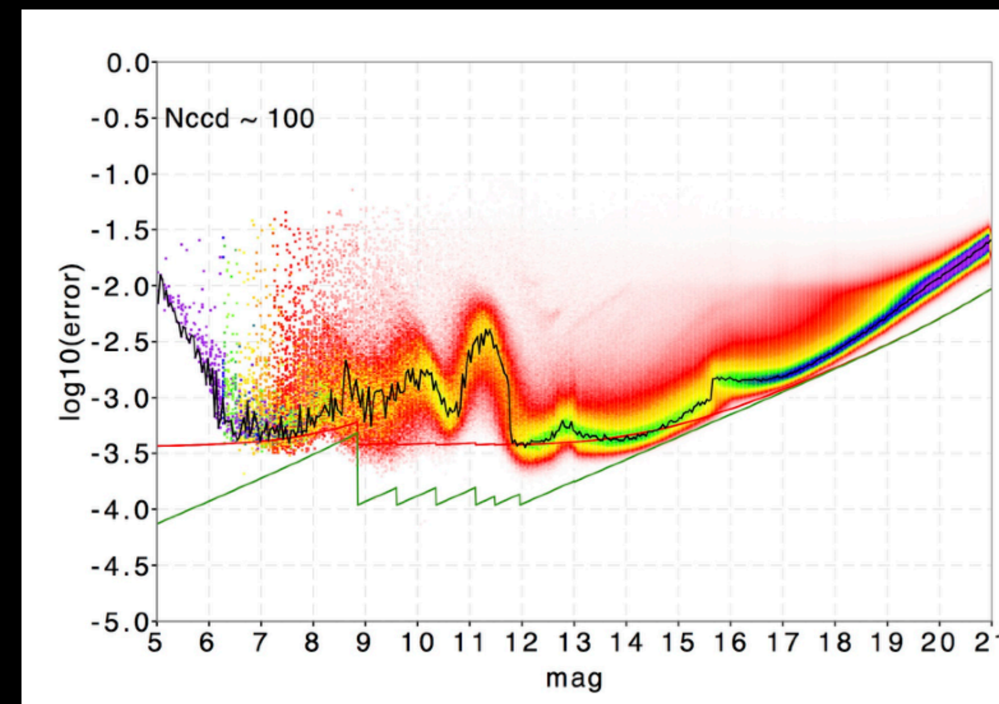
- zero_point = f(frame, X,Y, mag., color, …)

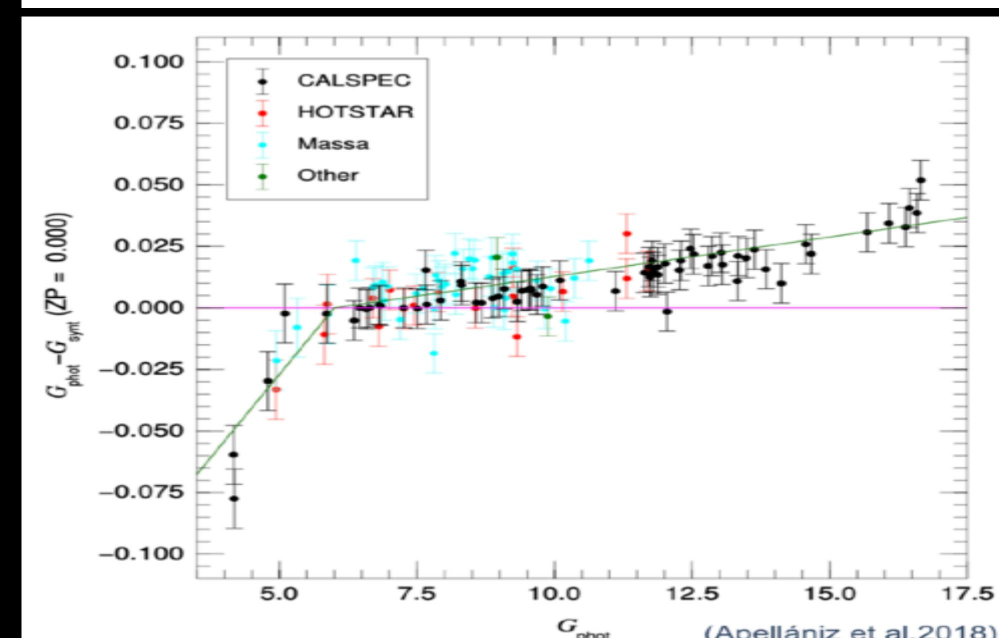
SCR in the era of LAMOST and Gaia

Stripe 82 colors;	2-5 mmag;	Yuan et al. (2015)
Skymapper DR2;	<10 mmag;	Huang, Yuan+, et al (2021)
Gaia DR2 colors;	~ 1 mmag;	Niu, Yuan & Liu (2021a)
Gaia EDR3 colors;	< 1 mmag;	Niu, Yuan & Liu (2021b)
Gaia EDR3 mags.;	< 1 mmag;	Yang, Yuan+ (2021)
J-PLUS DR2;	2-10 mmag;	Lopez-Sanjuan, Yuan+ (2021)
Stripe 82 ugriz;	2-5 mmag;	Huang & Yuan (2022)
PS1 DR1 grizy;	~2 mmag;	Xiao & Yuan (2022)
mini-JPAS 56 filters;	2-5 mmag;	Yuan et al. (2022)
SAGES DR1 u/v;	~5 mmag;	Yuan+ in prep.
SAGE DR1 g/r/i;	< 5 mag;	Xiao+ in prep.
J-PLUS DR3;	2-5 mmag;	Xiao+ in prep.

Gaia calibration errors as a function of Magnitude



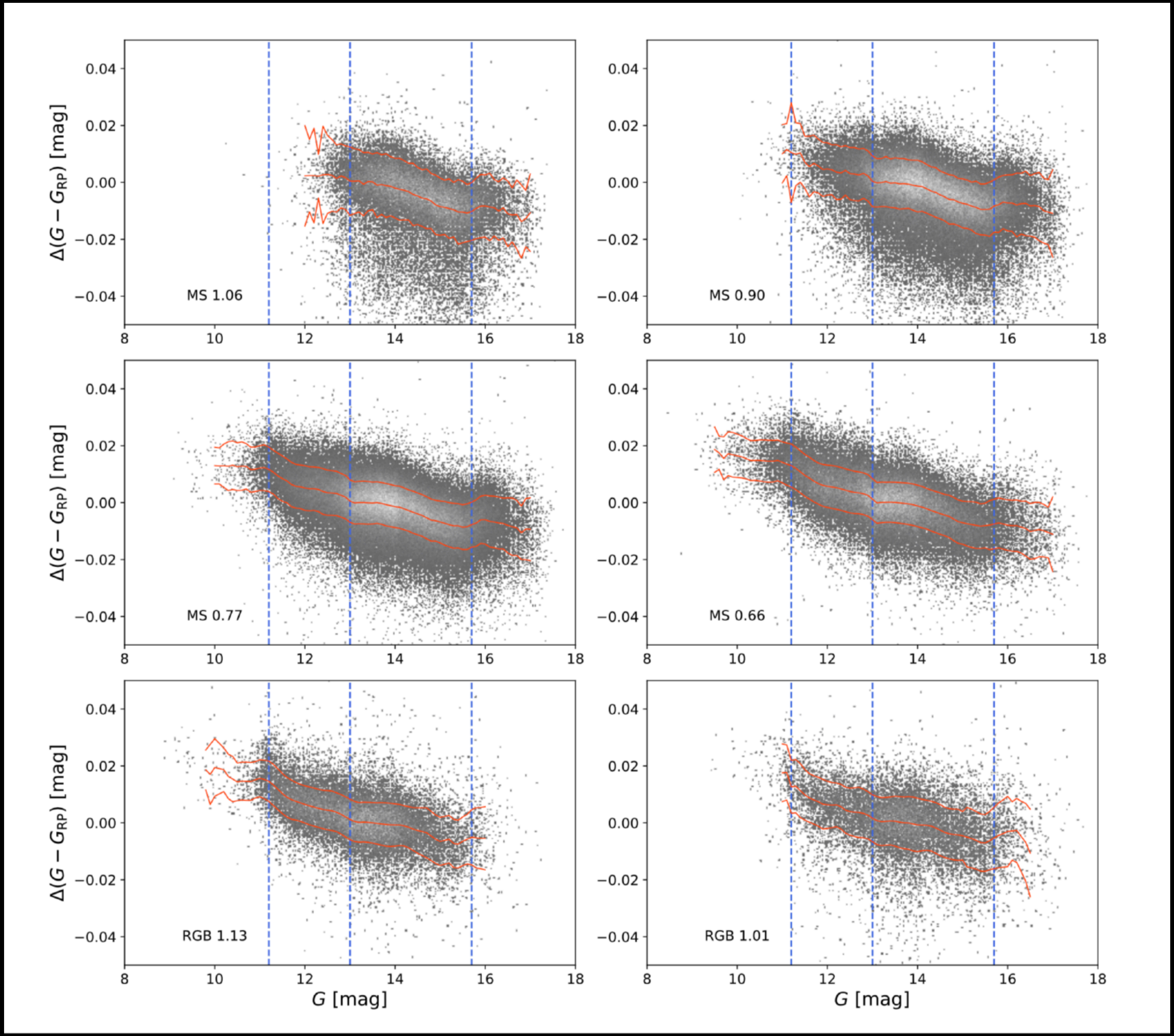




Color correction curves for different subsamples

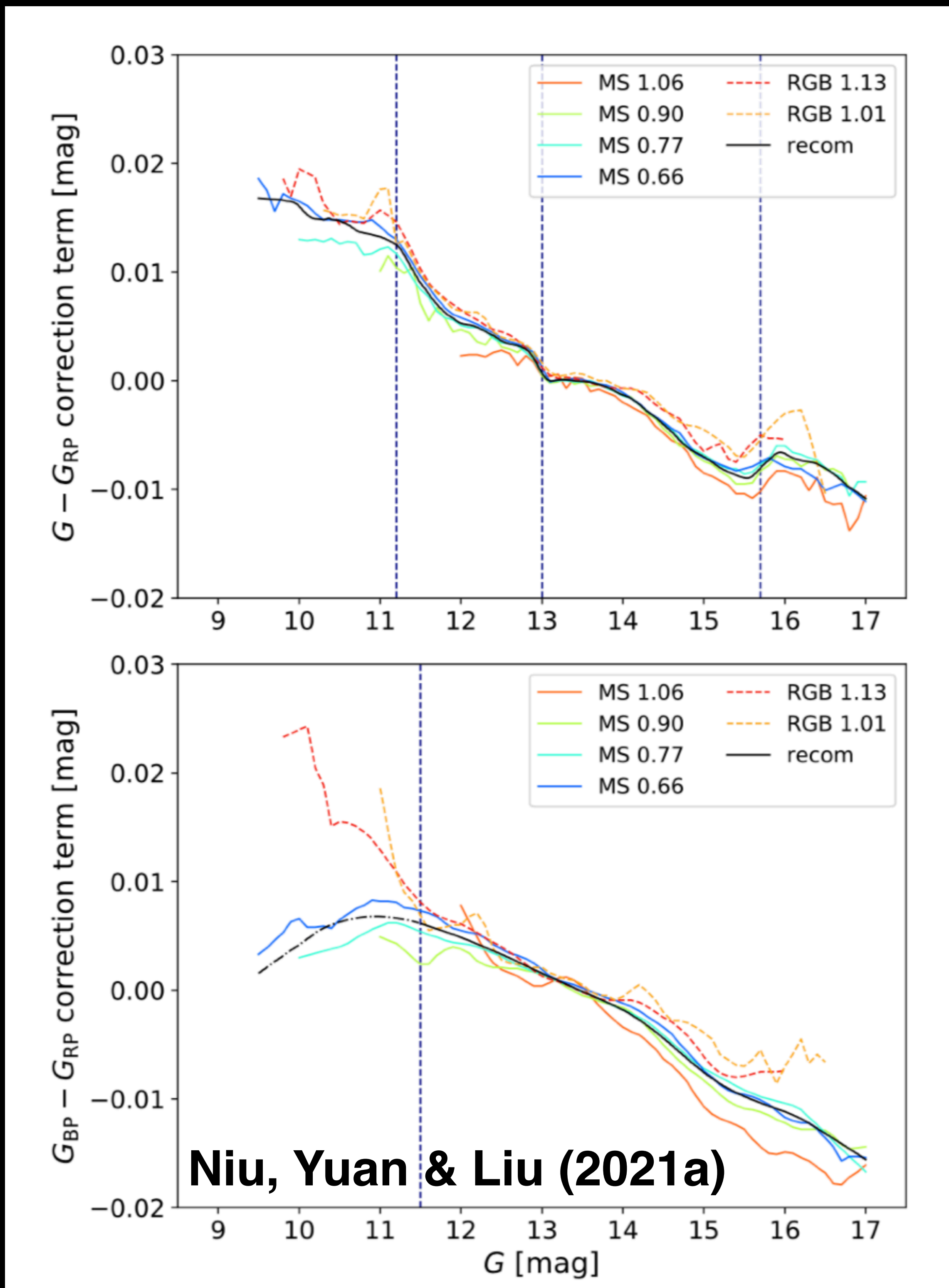
G-RP = f (Teff, FeH, Logg) + k*E(B-V)

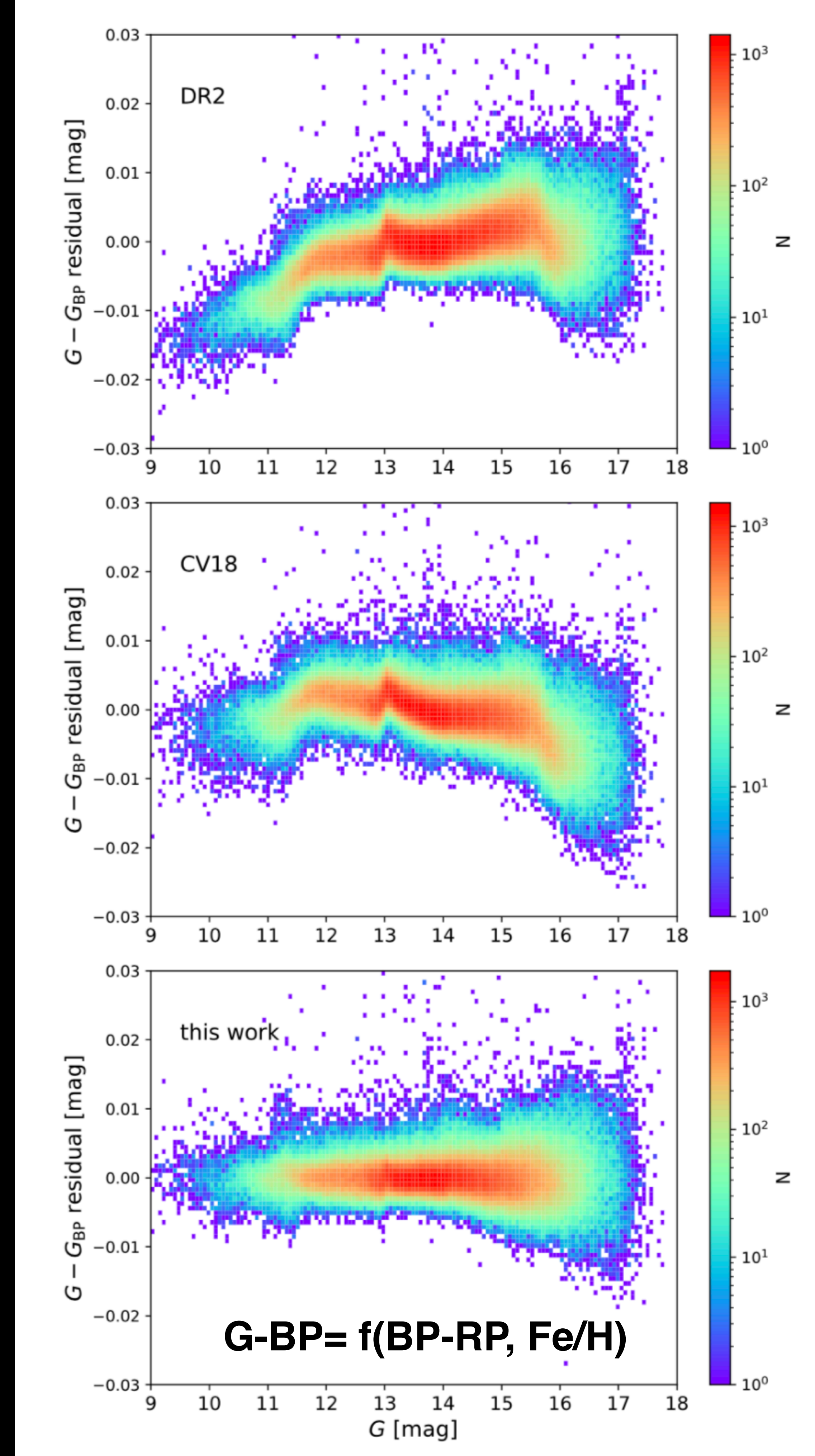
Reference sample:
13.3 < G < 13.7



Color correction curves for Gaia DR2

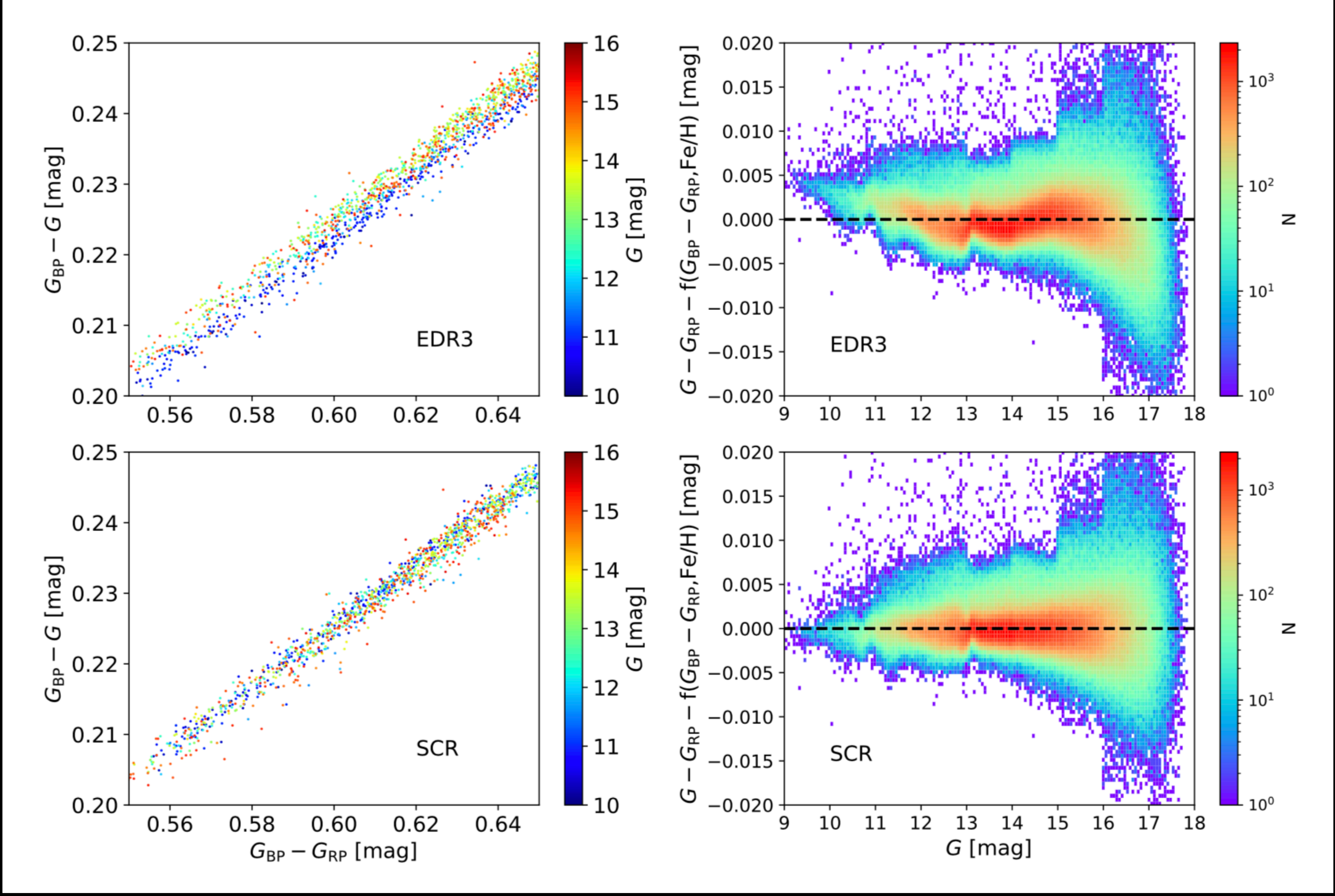
Color = f (Teff, FeH, Logg) + k*E(B-V)





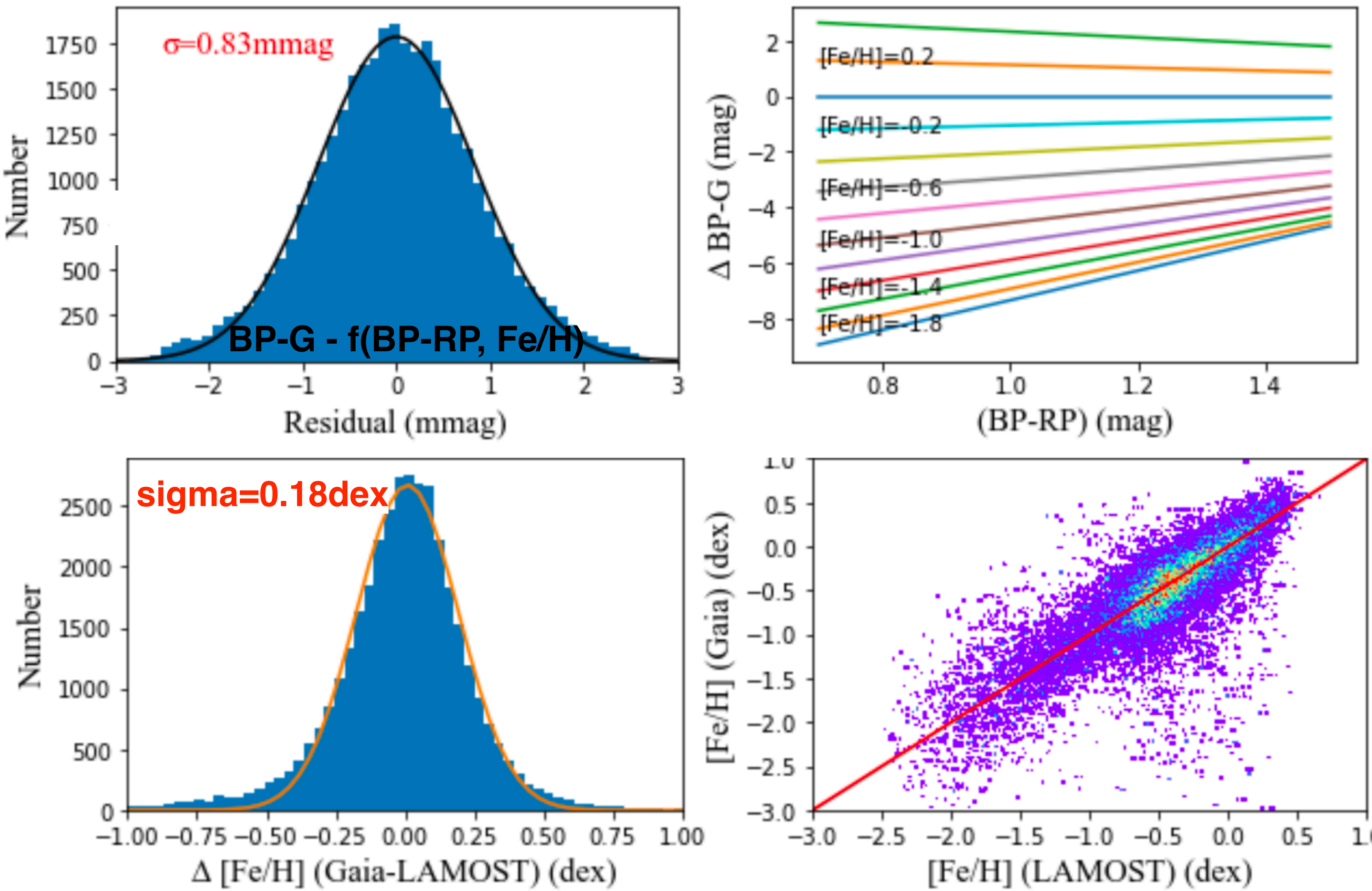
Gaia EDR3

Niu, Yuan & Liu (2021b)



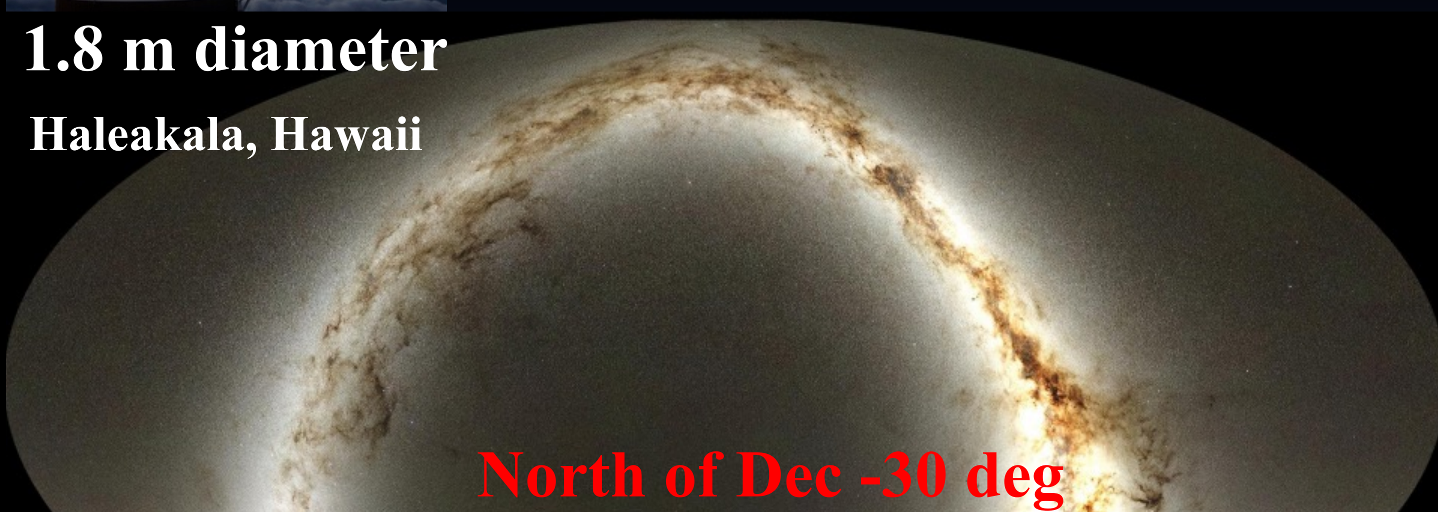
Photometric metallicities of Gaia stars

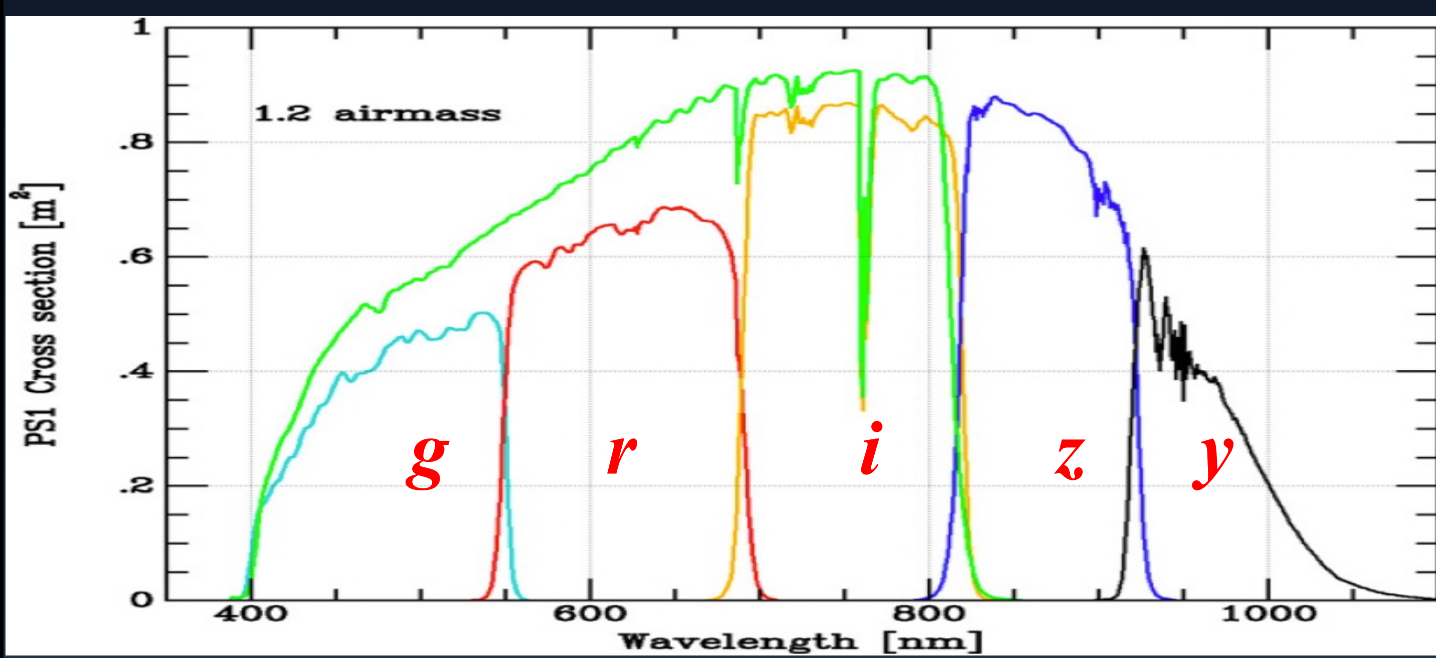
Xu et al. 2022



Improvement of the PS1 calibration

Pan-STARRS (PS1)



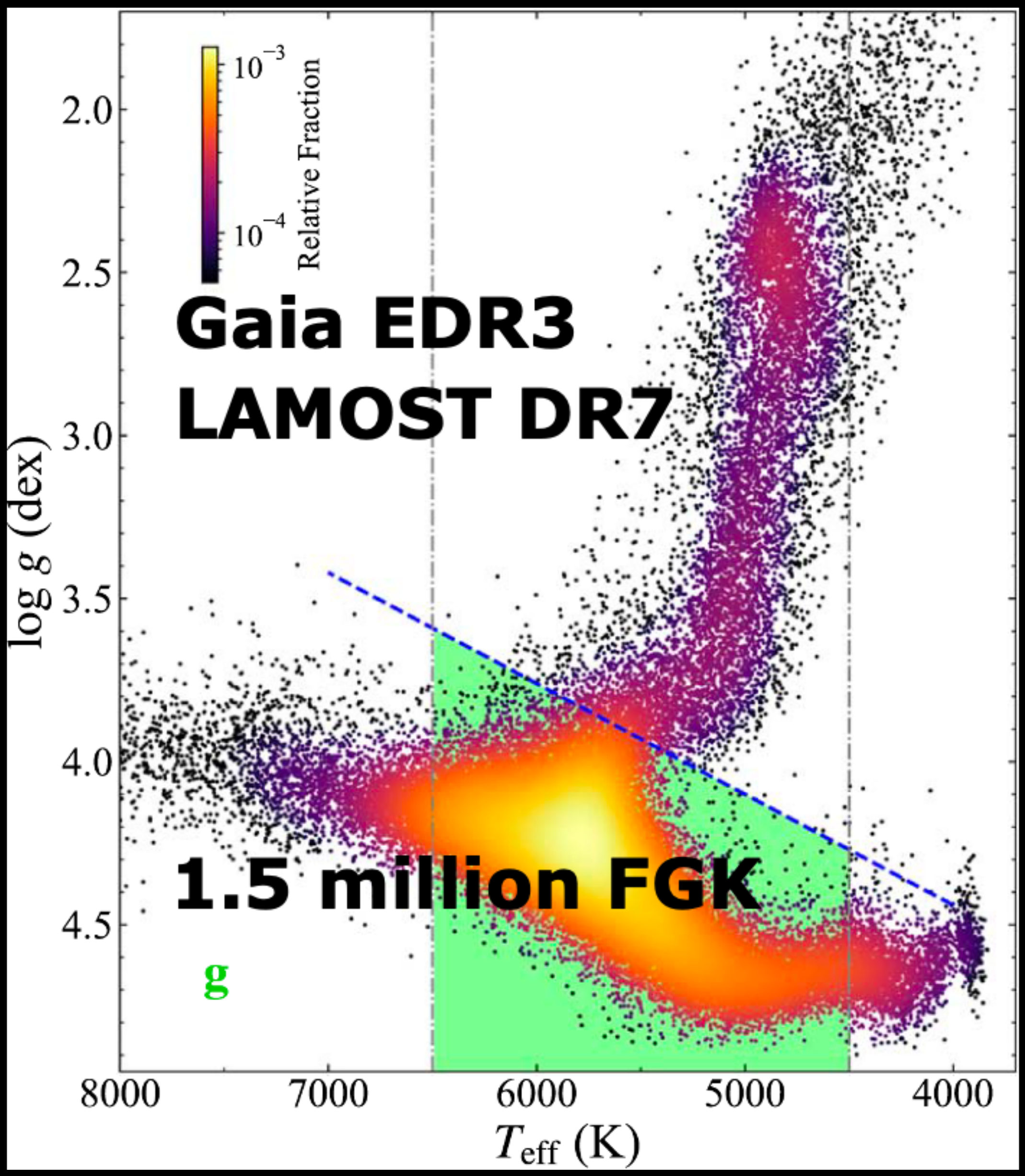


- 30,000 deg^2 in *grizy*
- FOV: 3.3 deg
- Ubercalibration

(Padmanabhan et al. 2008; Magnier et al. 2020)

- PS1 has been widely used as reference to others:
  - SDSS (Finkbeiner et al. 2016)
  - BASS (Zou et al. 2017; Zhou et al. 2018)
  - J-PLUS (Lopez-Sanjuan et al. 2019, 2021)
  - Type Ia supernovae (Scolnic et al. 2015; Brout et al. 2021)
  - …

Improvement of the PS1 calibration



Xiao & Yuan 2022

$$\begin{pmatrix} G_{\rm BP}-g \\ G_{\rm RP}-r \\ G_{\rm RP}-i \\ G_{\rm RP}-z \\ G_{\rm RP}-y \end{pmatrix}_0 = \begin{pmatrix} G_{\rm BP}-g \\ G_{\rm RP}-r \\ G_{\rm RP}-i \\ G_{\rm RP}-z \\ G_{\rm RP}-y \end{pmatrix} - \begin{pmatrix} R_{G_{\rm BP}-g} \\ R_{G_{\rm RP}-r} \\ R_{G_{\rm RP}-i} \\ R_{G_{\rm RP}-z} \\ R_{G_{\rm RP}-y} \end{pmatrix} \cdot E(G_{\rm BP}-G_{\rm RP})$$

Reddening

Intrinsic colors $= f(T_{\rm eff},\ [{\rm Fe/H}],\ \log g,\ \ldots)$

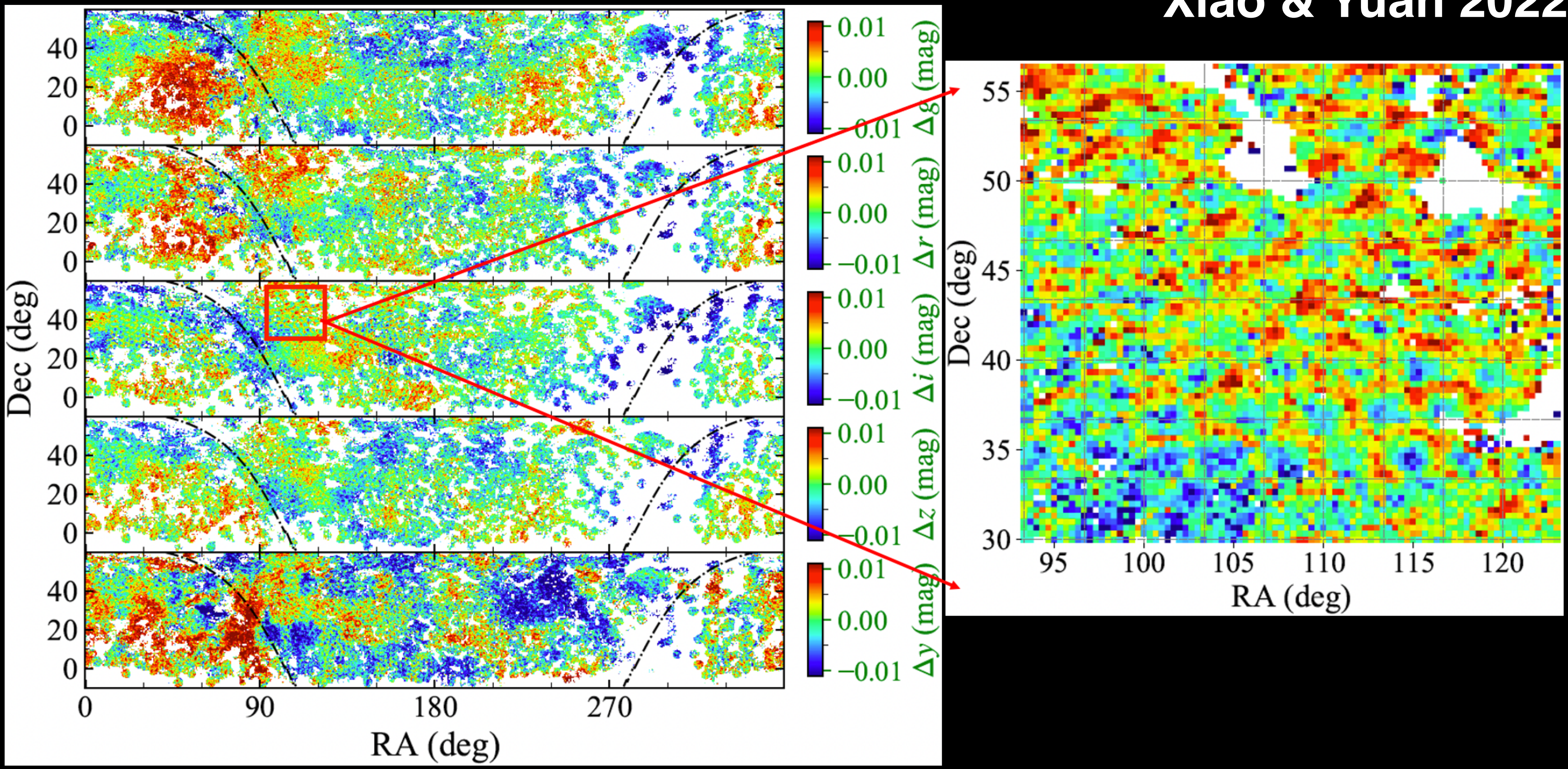
$M_{\rm mod}$ = G_{BP}/G_{RP} – f($T_{\rm eff}$, [Fe/H], log g, …) – Reddening

$$\Delta M = M_{\rm mod} - M_{\rm obs},\ \ M \in \{grizy\}$$

Improvement of the PS1 calibration

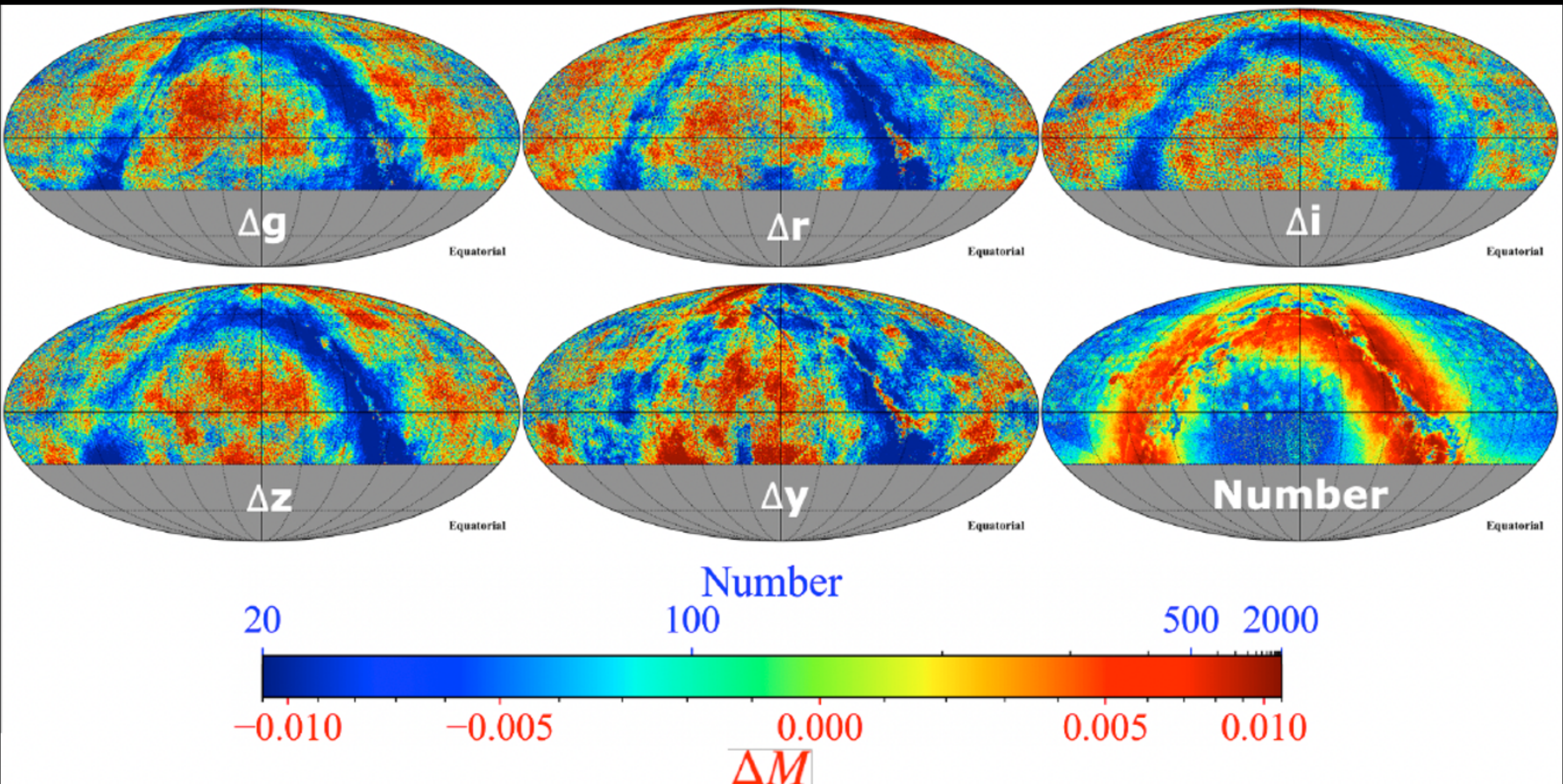
Spatial variations of PS1 calibration errors

Xiao & Yuan 2022



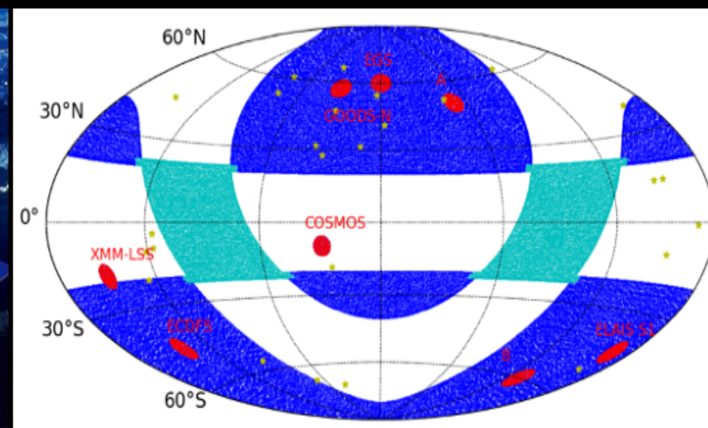
Correction maps of the full footprint

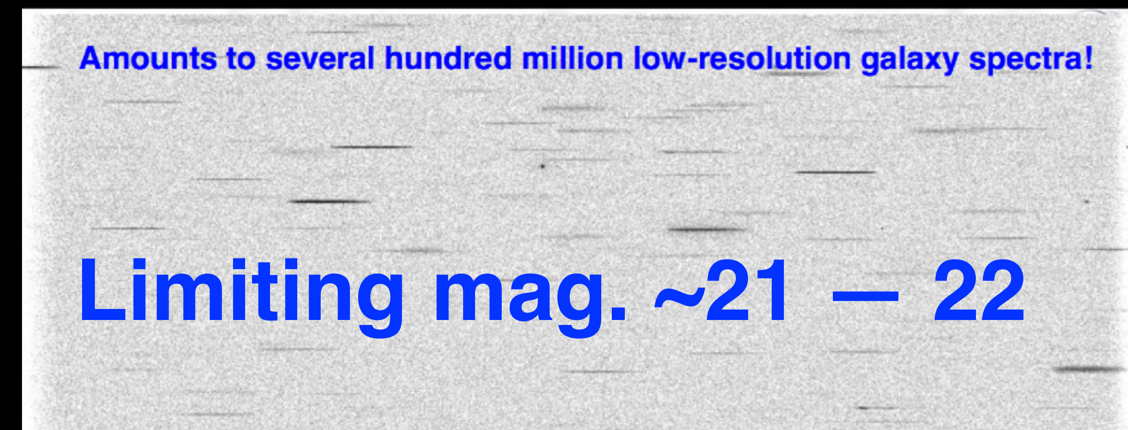
Xiao et al. in prep.

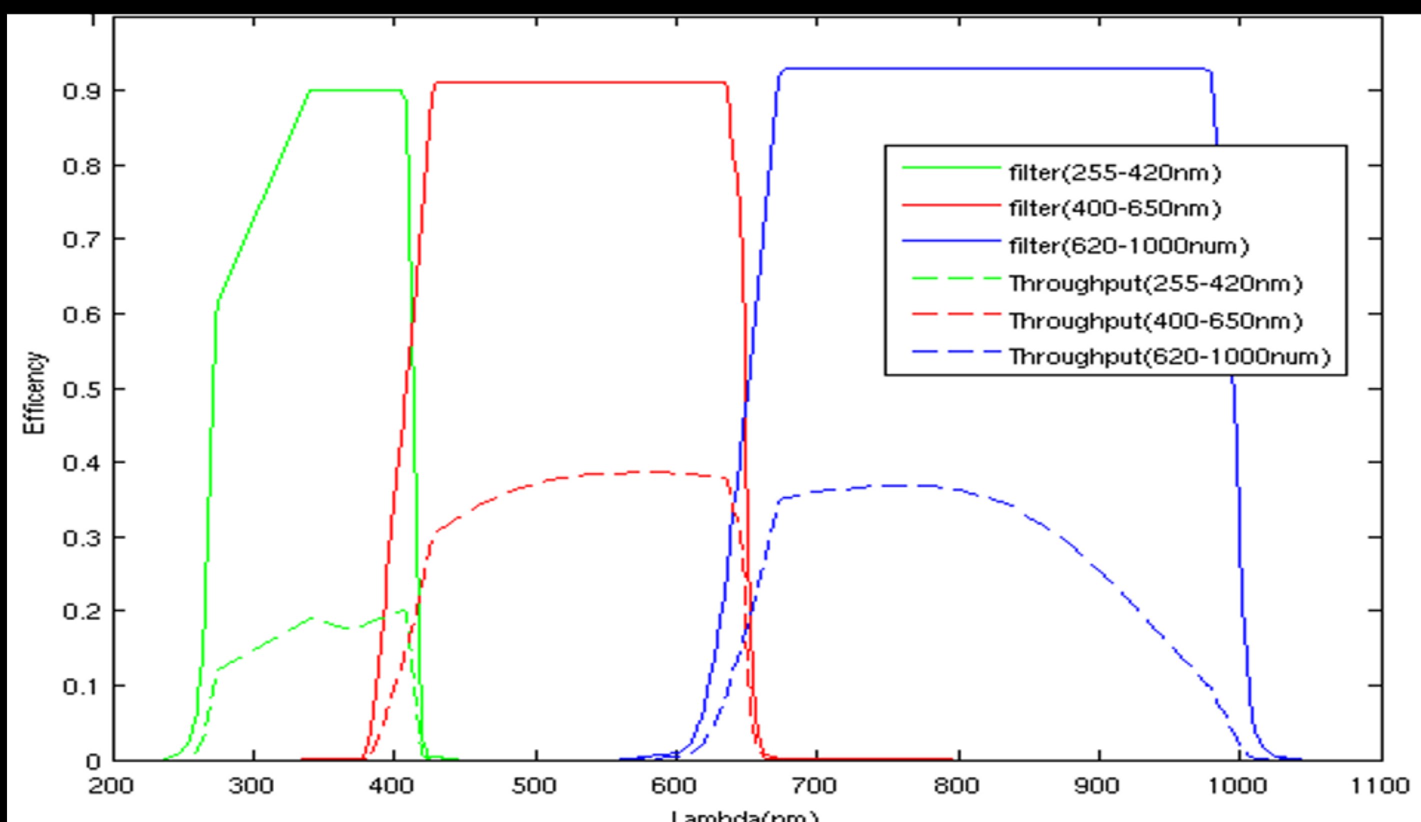


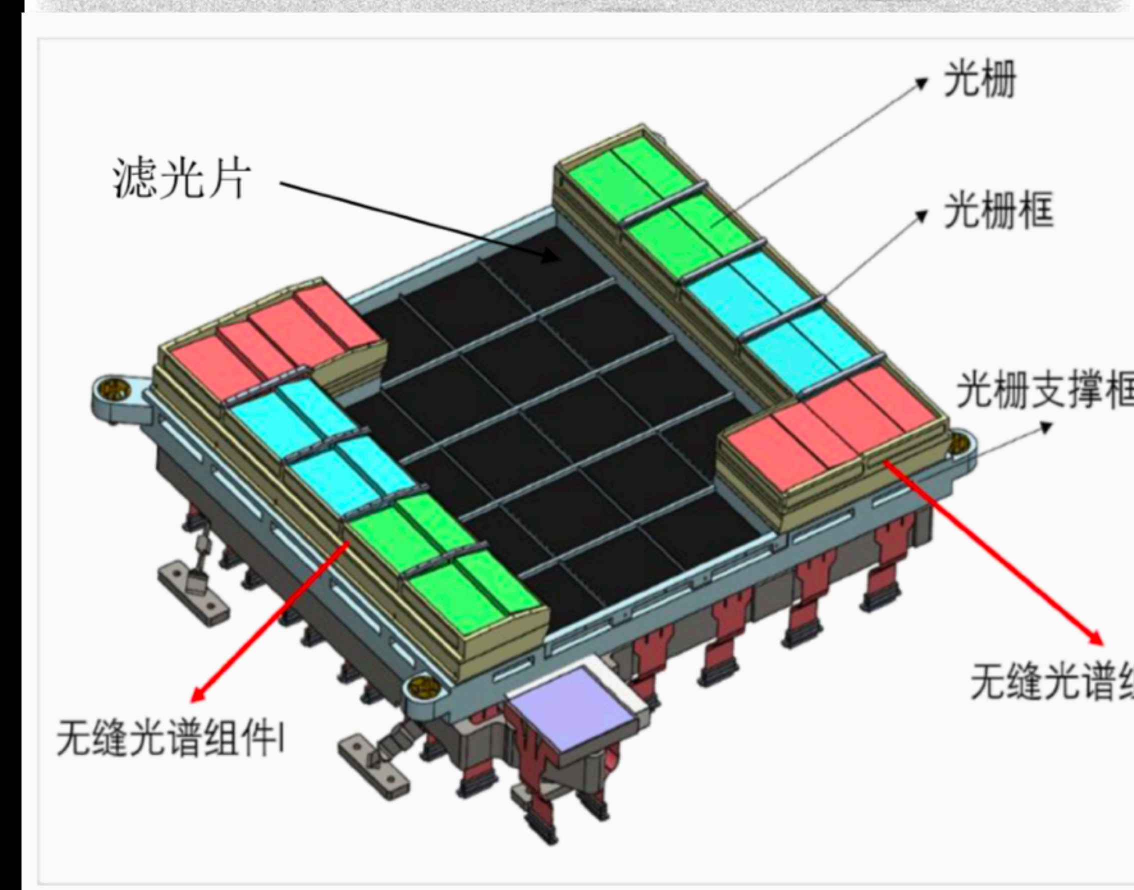
Wavelength calibration
of slit-less spectroscopic surveys

CSST slit-less spectroscopic survey



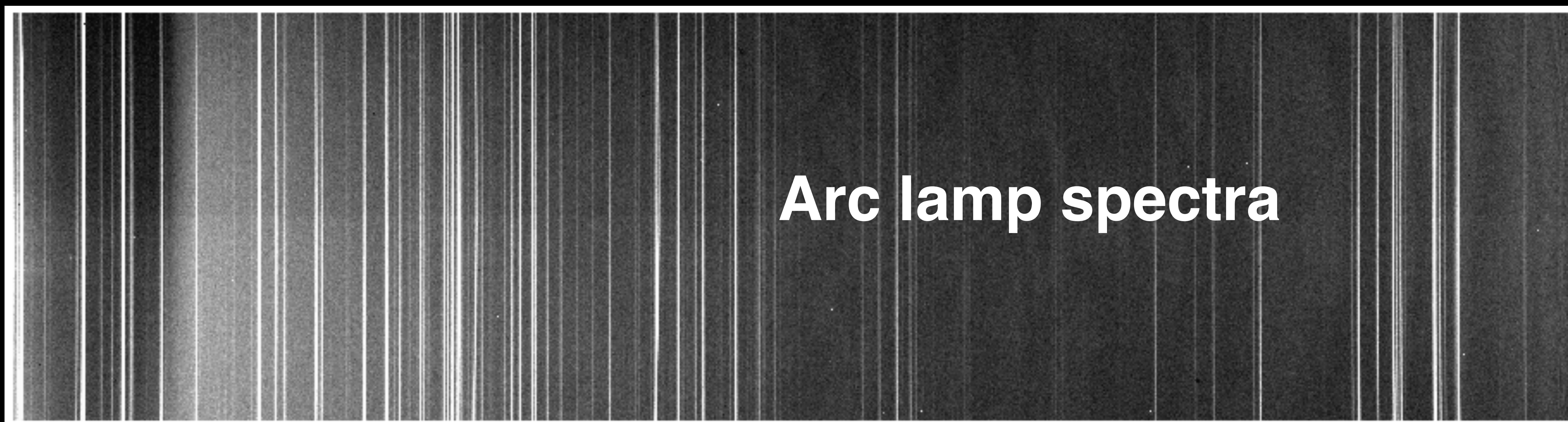






Challenges: spectral extraction; wavelength & flux calibrations

Wavelength calibration of long-slit/fiber spectra



Dispersion solution: lambda = f (X, Y)

Note: The wavelength zero-point usually shifts with time/environment

Wavelength calibration of slit-less spectroscopy

lambda = f(x,y, x’,y’)

(x’,y’) = f(ra, dec)

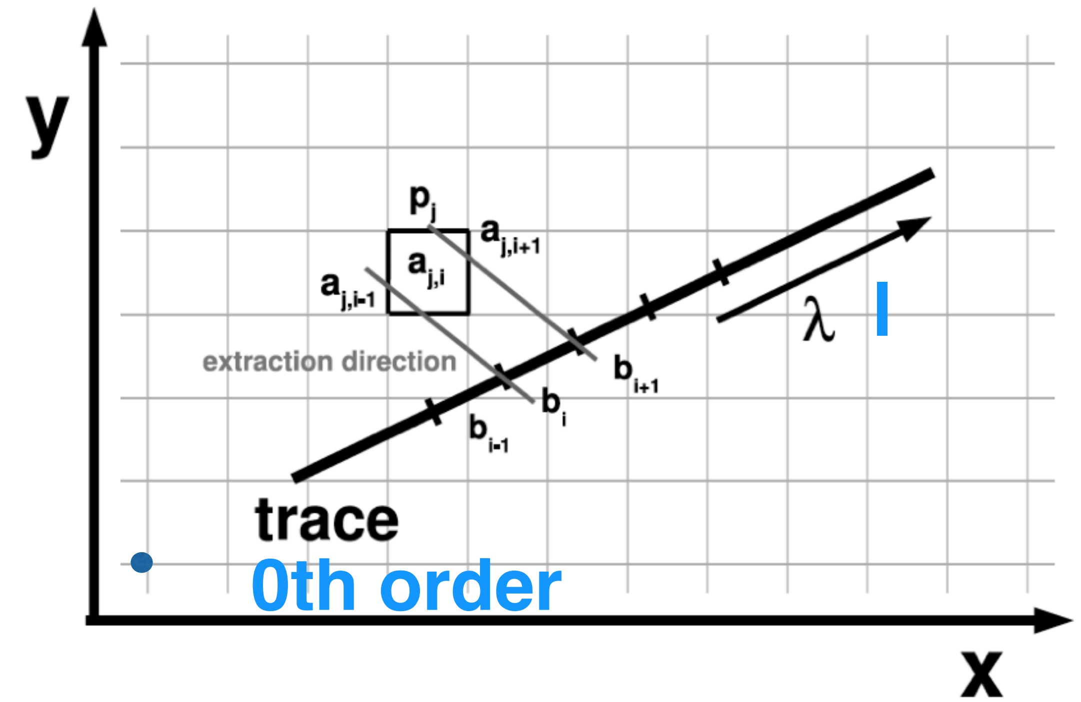
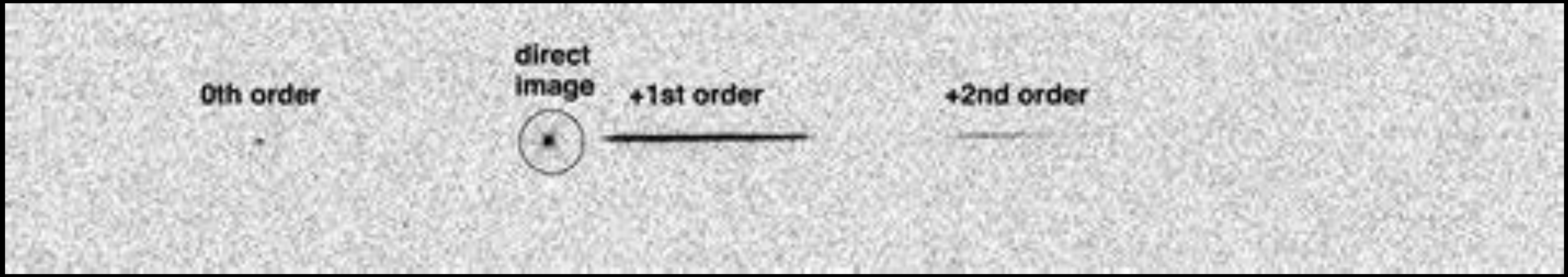


FIG. 2.—Projection of pixel p_j onto the set of spectral bins $[\ldots, b_{i-1}, b_i, b_{i+1}, \ldots]$. For the given trace and extraction direction (*gray, thin lines*), p_j contributes with the weight (=area) $a_{j,i-1}, a_{j,i}, a_{j,i+1}$ to the bins b_{i-1}, b_i, b_{i+1}.



Old approach

Compact, bright, and stable targets in a sparse field and with a good grid of emission lines are typically chosen (Pasquali+06)

- **Planetary nebulae in external galaxies**
- **Wolf-Rayet stars**
- **Ae stars, Be stars**
- **Cataclysmic variable stars**
- **Young stellar objects**
- **AGNs**

A new star-based approach

Yuan et al. 2021

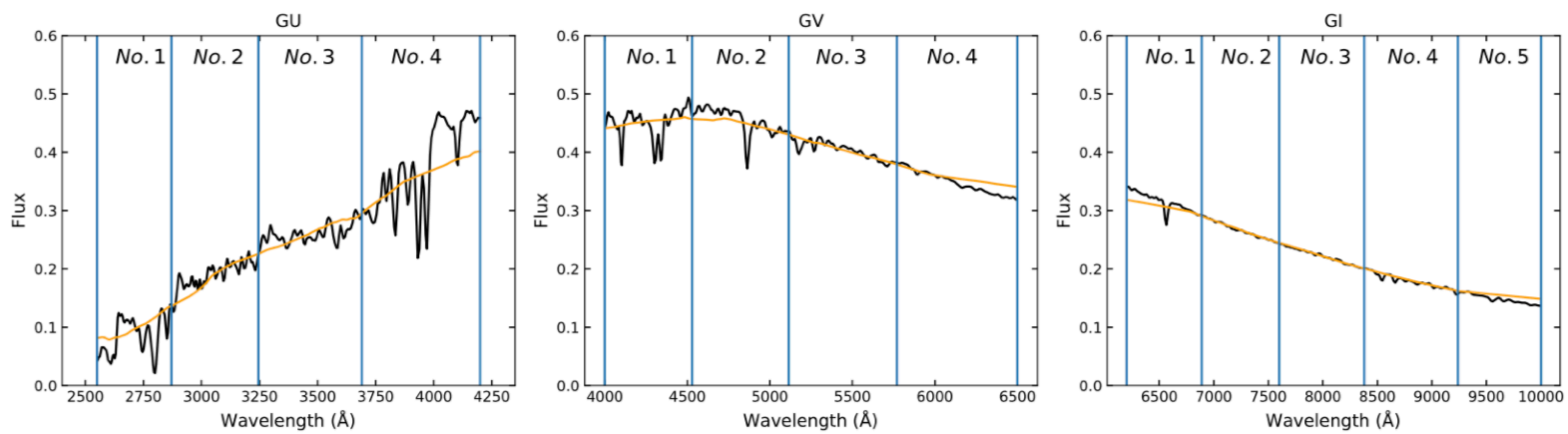


Fig. 1: Example of segment spectrum from HD196218 ($T_{\rm eff} = 6207$ K, $\log g = 4.11$ dex and [Fe/H] $= -0.19$ dex). The black and yellow lines are the degraded (R = 250) NGSL spectrum and its continuum obtained by the simple approach in Paper I, respectively. The boundaries between adjacent segments (marked

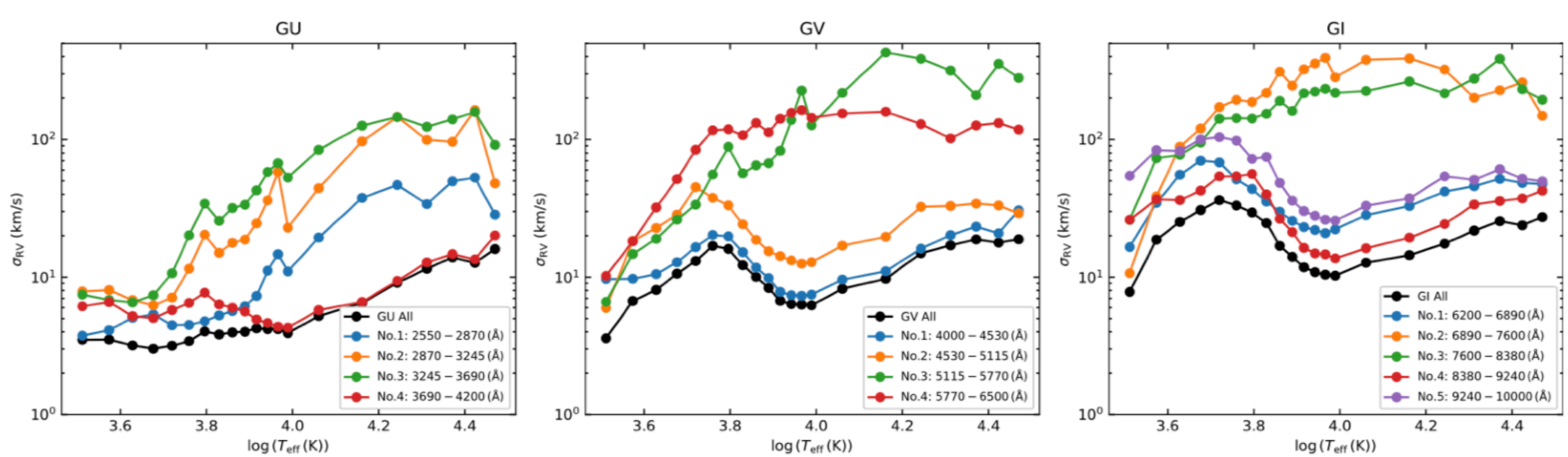


Fig. 2: The median values of $\sigma_{\rm RV}$ as a function of $T_{\rm eff}$ at SNR = 100 for different segments. The values for the whole GU/GV/GI band are also plotted for comparison.

Expected precision

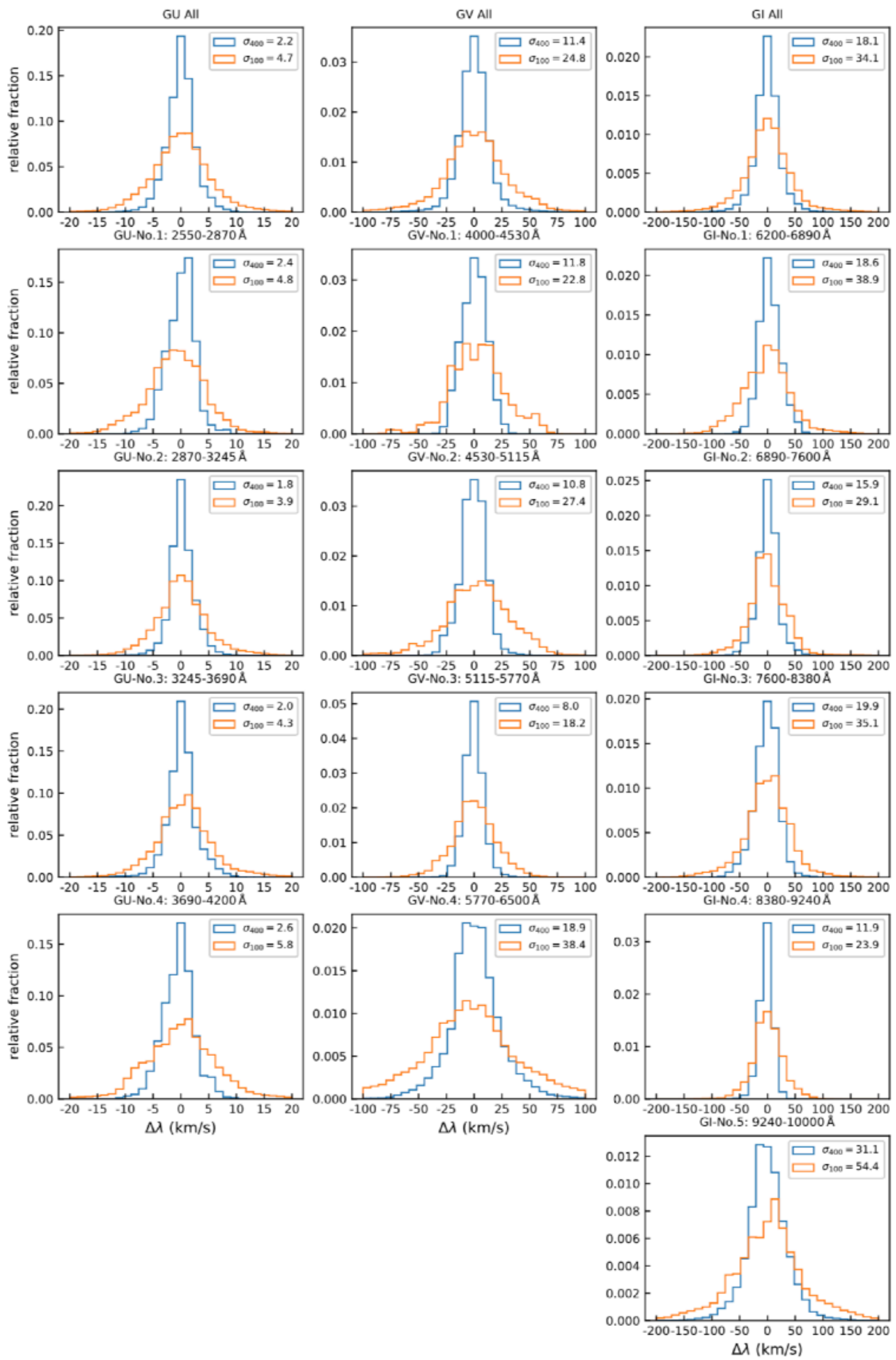
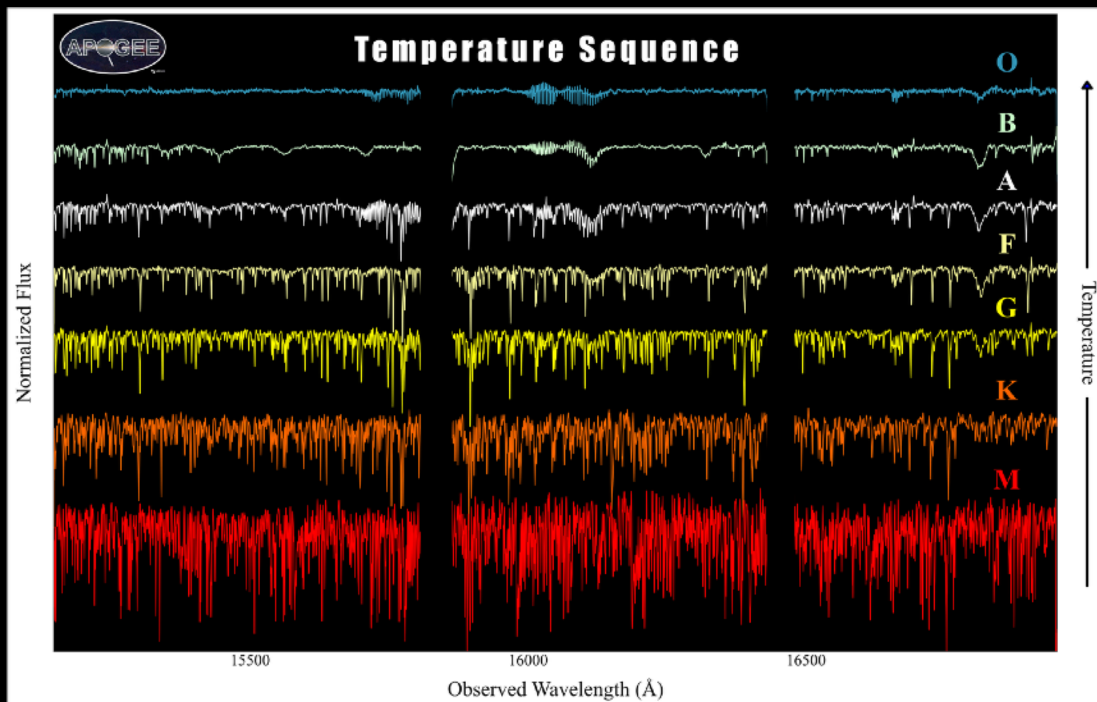
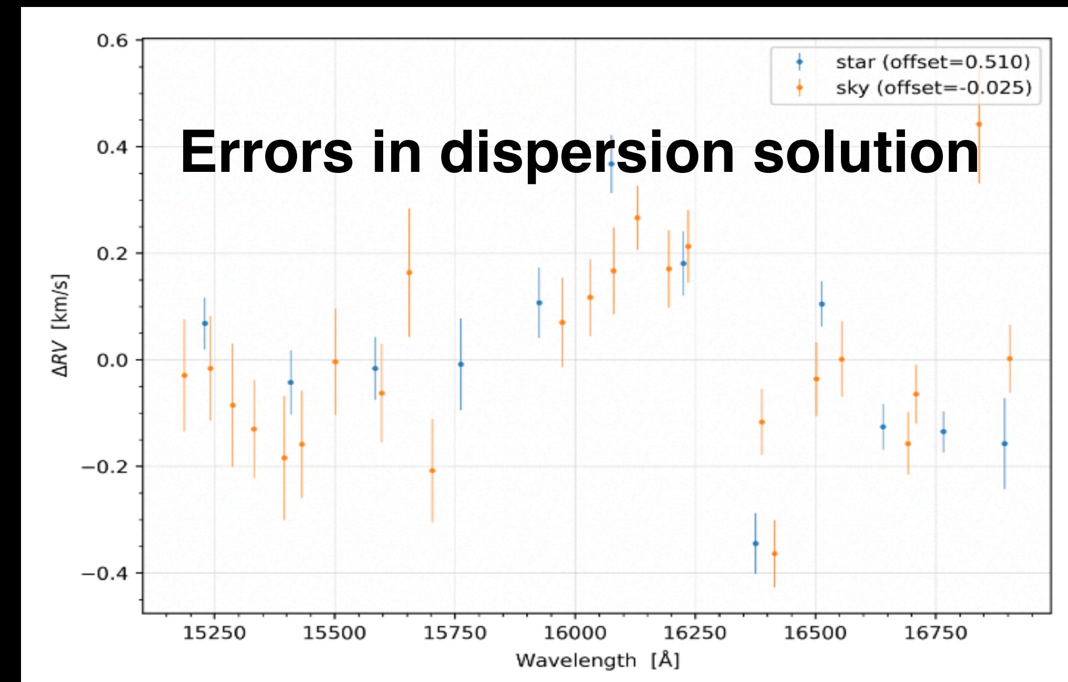


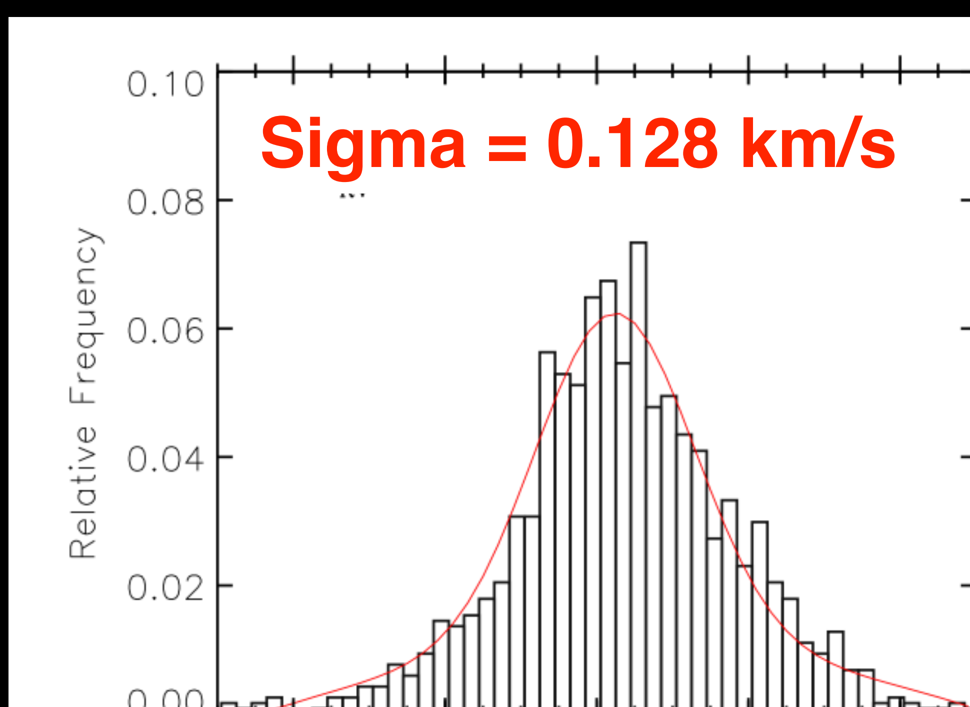
Table 2: Wavelength calibration errors for the GU/GV/GI bands at N=100, 400.

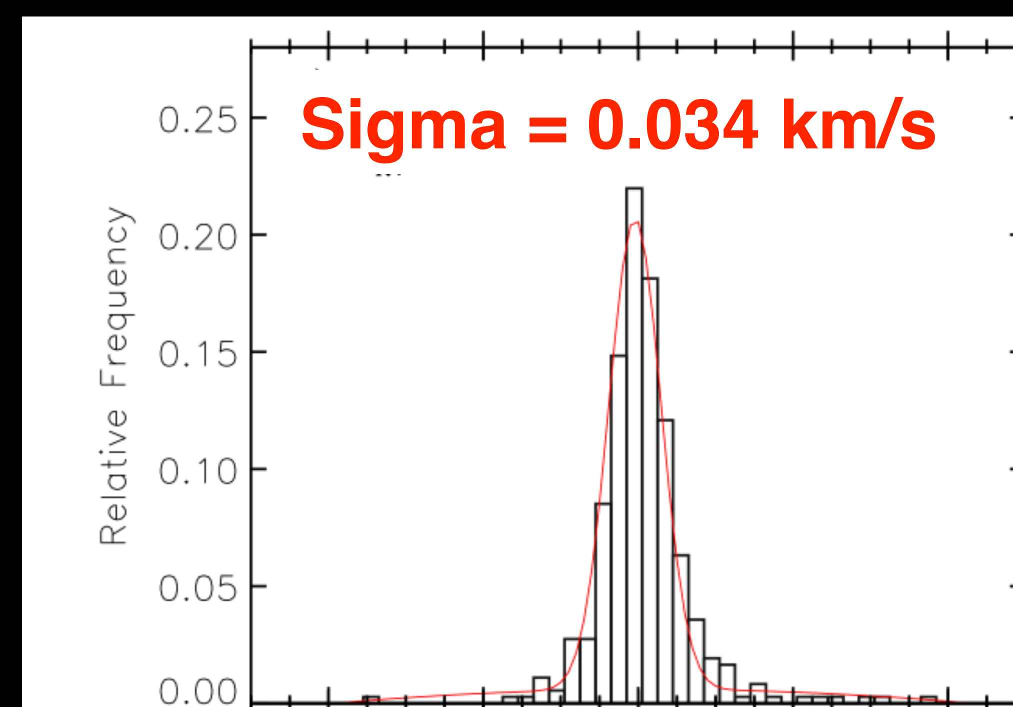
Wavelength Range (Å)	Dispersions of $\Delta\lambda$ ($\mathrm{km\,s^{-1}}$) N = 100	N = 400
GU-All: 2550-4200	4.7	2.2
GU-No.1: 2550-2870	4.8	2.4
GU-No.2: 2870-3245	3.9	1.8
GU-No.3: 3245-3690	4.3	2.0
GU-No.4: 3690-4200	5.8	2.6
GV-All: 4000-6500	24.8	11.4
GV-No.1: 4000-4530	22.8	11.8
GV-No.2: 4530-5115	27.4	10.8
GV-No.3: 5115-5770	18.2	8.0
GV-No.4: 5770-6500	38.4	18.9
GI-All: 6200-10000	34.1	18.1
GI-No.1: 6200-6890	38.9	18.6
GI-No.2: 6890-7600	29.1	15.9
GI-No.3: 7600-8380	35.1	19.9
GI-No.4: 8380-9240	23.9	11.9
GI-No.5: 9240-10000	54.4	31.1

Applying to APOGEE









delta(RV)

delta(RV)

Flux calibration of slit-less spectroscopic surveys

Flux calibration

- F(lambda)
  - 3D flat cube = f(x,y, lambda)
  - Hubble: 1-2% within given area and wavelength range
  - CSST?

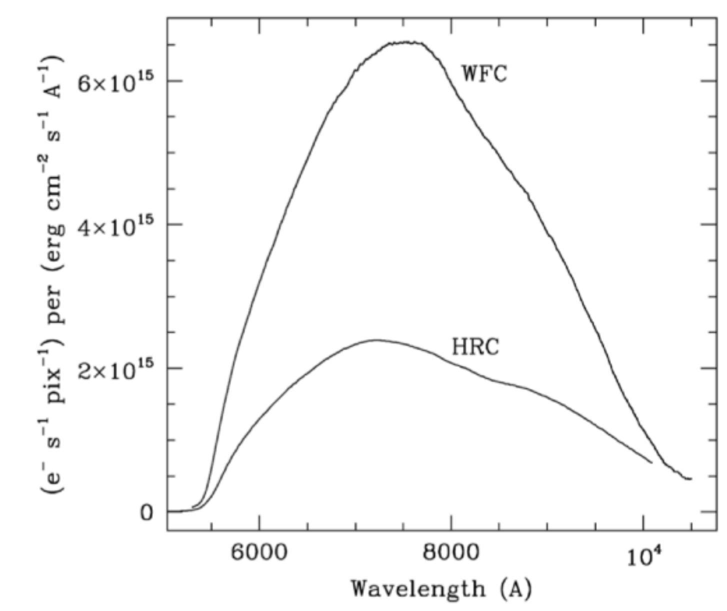


FIG. 13.—Sensitivity functions of the grism first order when coupled with the WFC and the HRC.

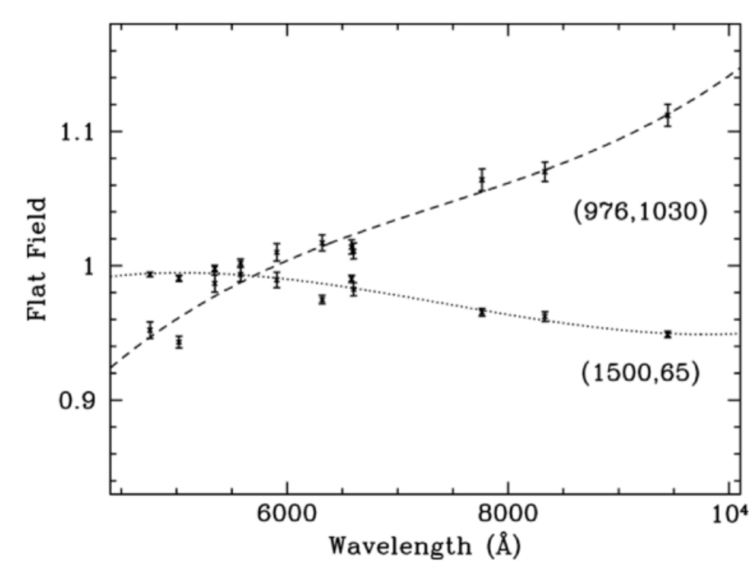


FIG. 5.—Flat-field values as a function of wavelength for two ACS/WFC pixels (CCD no. 1) derived from direct-image flat fields. The coefficients of the polynomial fits (shown as lines) to the data are stored in the flat-field cube.

Calibrating slit-less spectra to ~1% precision

- Predicting colors, magnitudes to ~1% precision for millions of stars with Gaia + LAMOST-like data

- Predicting SEDs (R250) to ~1% with precise stellar parameters, normalized spectra, multi-band photometry for millions of stars

- Flat cube f(x,y, lambda) can then be well constructed

- Gaia spectrophotometry

Predicting R200 SEDs with normalized R2000 spectra

Yang et al. in prep.

We use the LAMOST normalized spectra of $R = 2000$ (4000–7000Å) to predict the CSST SEDs of $R = 200$ over the whole wavelength (2550—10500Å)

From observable to observable

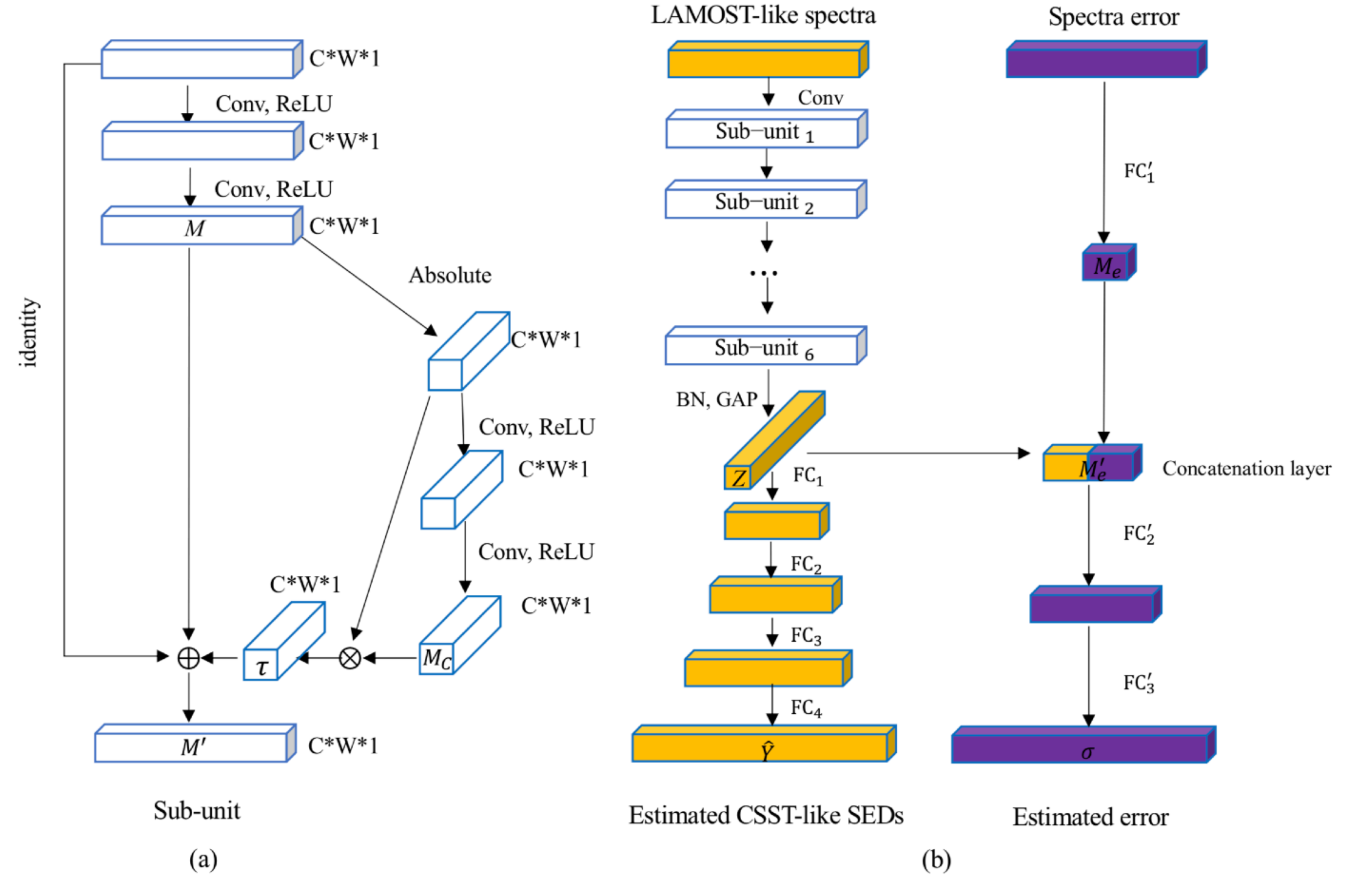
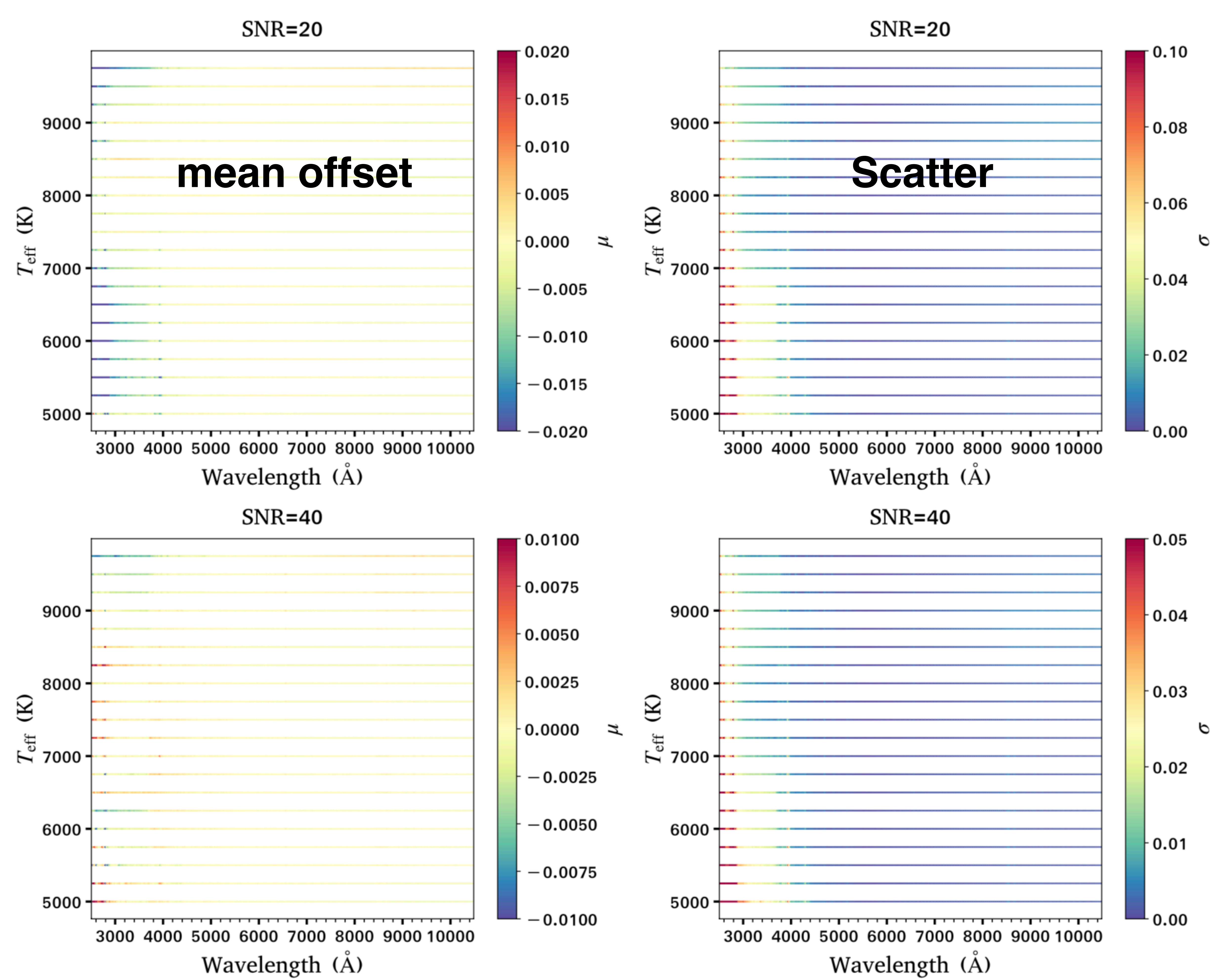
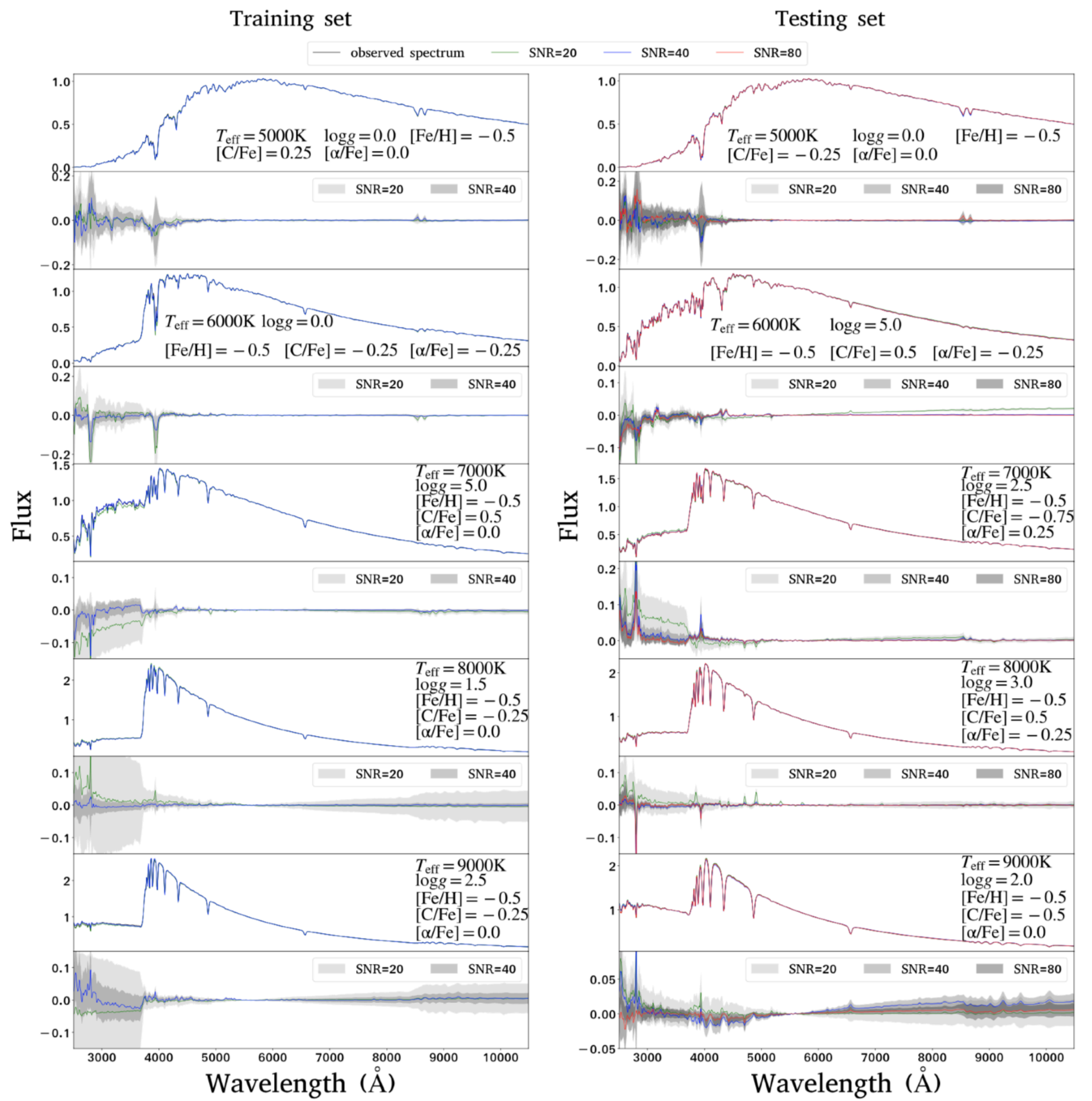


Fig. 1. (a) A sub-unit of the proposed network, where C, W, and 1 in $C * W * 1$ are the indicators of the number of channels, width, and height of the feature map, respectively. (b) Overall architecture of the proposed network.



SNR=20
mean offset
SNR=20
Scatter
SNR=40
SNR=40
$T_{\rm eff}$ (K)
Wavelength (Å)
μ
σ

Examples


Training set
Testing set
observed spectrum
SNR=20
SNR=40
SNR=80
$T_{\rm eff}=5000$K logg=0.0 [Fe/H]=−0.5 [C/Fe]=0.25 [α/Fe]=0.0
$T_{\rm eff}=5000$K logg=0.0 [Fe/H]=−0.5 [C/Fe]=−0.25 [α/Fe]=0.0
$T_{\rm eff}=6000$K logg=0.0 [Fe/H]=−0.5 [C/Fe]=−0.25 [α/Fe]=−0.25
$T_{\rm eff}=6000$K logg=5.0 [Fe/H]=−0.5 [C/Fe]=0.5 [α/Fe]=−0.25
$T_{\rm eff}=7000$K logg=5.0 [Fe/H]=−0.5 [C/Fe]=0.5 [α/Fe]=0.0
$T_{\rm eff}=7000$K logg=2.5 [Fe/H]=−0.5 [C/Fe]=−0.75 [α/Fe]=0.25
$T_{\rm eff}=8000$K logg=1.5 [Fe/H]=−0.5 [C/Fe]=−0.25 [α/Fe]=0.0
$T_{\rm eff}=8000$K logg=3.0 [Fe/H]=−0.5 [C/Fe]=0.5 [α/Fe]=−0.25
$T_{\rm eff}=9000$K logg=2.5 [Fe/H]=−0.5 [C/Fe]=−0.25 [α/Fe]=0.0
$T_{\rm eff}=9000$K logg=2.0 [Fe/H]=−0.5 [C/Fe]=−0.5 [α/Fe]=0.0
Flux
Wavelength (Å)

Summary

- SCR + Gaia + LAMOST/… are very promising to provide millions of precise (1-2%) standard stars in different filters and colors

- A number of surveys have been re-calibrated to a precision of a few mmag, opening up new discovery space

- With SCR, FGCM and other methods and more data, mmag precision photometric calibration is on the way

- Using millions of stars as standards, precise wavelength and flux calibration is possible for the CSST slit-less spectroscopic survey