Passband reconstruction and Revised Gaia Data Release 2 passbands

Michael Weiler

Universitat de Barcelona

Reconstructing passbands: Definitions

$$c = \int_{\lambda_0}^{\lambda_1} p(\lambda)\, s(\lambda)\, \mathrm{d}\lambda$$

observed count rate

(*Gaia* DR1/2: photoelectrons per second per 0.7278 m^2)

spectral photon distribution

(photons per second per unit of wavelength per 0.7278 m^2)

passband

(photoelectrons per photon as a function of wavelength)

Reconstructing passbands: The problem

Reconstruction of a passband:
From a set of N sources with spectral photon distributions (SPDs) and count rates given, find passband.

System of N equations to be solved for $p(\lambda)$:

$$c_i = \int_{\lambda_0}^{\lambda_1} p(\lambda)\, s_i(\lambda)\, \mathrm{d}\lambda \,, \quad i = 1, \ldots, N$$

Approach:
Make use of square integrability of all involved functions on $I = [\,\lambda_0, \lambda_1\,]$ and make it vector calculus

Reconstructing passbands: The method

Develop SPDs in basis: $$s_i(\lambda) = \sum_{j=1}^{\infty} b_{ij}\, \psi_j(\lambda)$$

basis vectors

which is orthonormal: $$\int_{\lambda_0}^{\lambda_1} \psi_k(\lambda) \cdot \psi_l(\lambda)\, \mathrm{d}\lambda = \langle\, \psi_k \,|\, \psi_l \,\rangle = \delta_{kl}$$

scalar product

For N sources, with properly chosen basis vectors, this becomes

$$s_i(\lambda) = \sum_{j=1}^{M} a_{ij}\, \varphi_j(\lambda)\,, \quad 1 \leq M \leq N$$

▷ Suitable basis functions $\varphi_j(\lambda)$ can be constructed using functional principal component analysis.

Reconstructing passbands: The method

$$c_i = \int_{\lambda_0}^{\lambda_1} p(\lambda)\, s_i(\lambda)\, \mathrm{d}\lambda\,, \quad i = 1, \ldots, N$$

$$s_i(\lambda) = \sum_{j=1}^{M} a_{ij}\, \varphi_j(\lambda)\,, \quad 1 \le M \le N$$

$$\mathbf{c} = \mathbf{A}\,\mathbf{p}$$

N - vector of count rates

N x M matrix of a_{ij}

M - vector of $p_j = \langle p \,|\, \varphi_j \rangle$

Projection of the passband on the calibration SPDs

"parallel component" of the passband:

$$p_{\|}(\lambda) = \sum_{j=1}^{M} p_j\, \varphi_j(\lambda)$$

Reconstructing passbands: General results

A freedom remains in the passband:

Any function $p_\perp(\lambda)$ such that $\langle p_\perp \,|\, s_i \rangle = 0\,, \quad i = 1, \ldots, N$ can be added

Passband is the sum of two functions:

$$p(\lambda) = p_{||}(\lambda) + p_\perp(\lambda)$$

With $p_{||}(\lambda)$ determined by calibration sources and with

$$\langle p_{||} \,|\, p_\perp \rangle = 0$$

The “orthogonal component” of the passband $p_\perp(\lambda)$ is unconstrained by the calibration sources and needs to be guessed.

Passband is only constrained on space spanned by the calibration spectra

⇨ *Reliable synthetic photometry only for spectra which are a linear combination of the calibration spectra*

Reconstructing passbands: Advanced guessing

Guessing the orthogonal component:

Take guess $p_{ini}(\lambda)$ based on expectations *(simulated/lab measurements of quantum efficiencies, mirror reflectance,...)*

and modify it: $$p(\lambda) = \left(\sum_{k=0}^{K-1} \alpha_k \, \phi_k(\lambda) \right) \cdot p_{ini}(\lambda)$$

fixing $p_{\|}(\lambda)$: $$p_j = \left\langle \left(\sum_{k=0}^{K-1} \alpha_k \, \phi_k(\lambda) \right) \cdot p_{ini}(\lambda) \,\middle|\, \varphi_j \right\rangle , \quad j = 1, \ldots, M$$

provides linear system: $$\mathbf{p} = \mathbf{M} \, \boldsymbol{\alpha}$$

$\boldsymbol{\alpha}$ ← K coefficients for modification

$\mathbf{p}$ ← M - vector solution

$\mathbf{M}$ ← M x K matrix with $M_{j,k} = \langle \phi_k \cdot p_{ini} \,|\, \varphi_j \rangle$

Reconstructing passbands: What remains

Find a modification of p_{ini} such that p is

- ▷ bound to [0,1]
- ▷ sufficiently smooth
- ▷ reproduces colour-colour relationships
- ▷ has a "reasonable" shape

Suitable modification models:

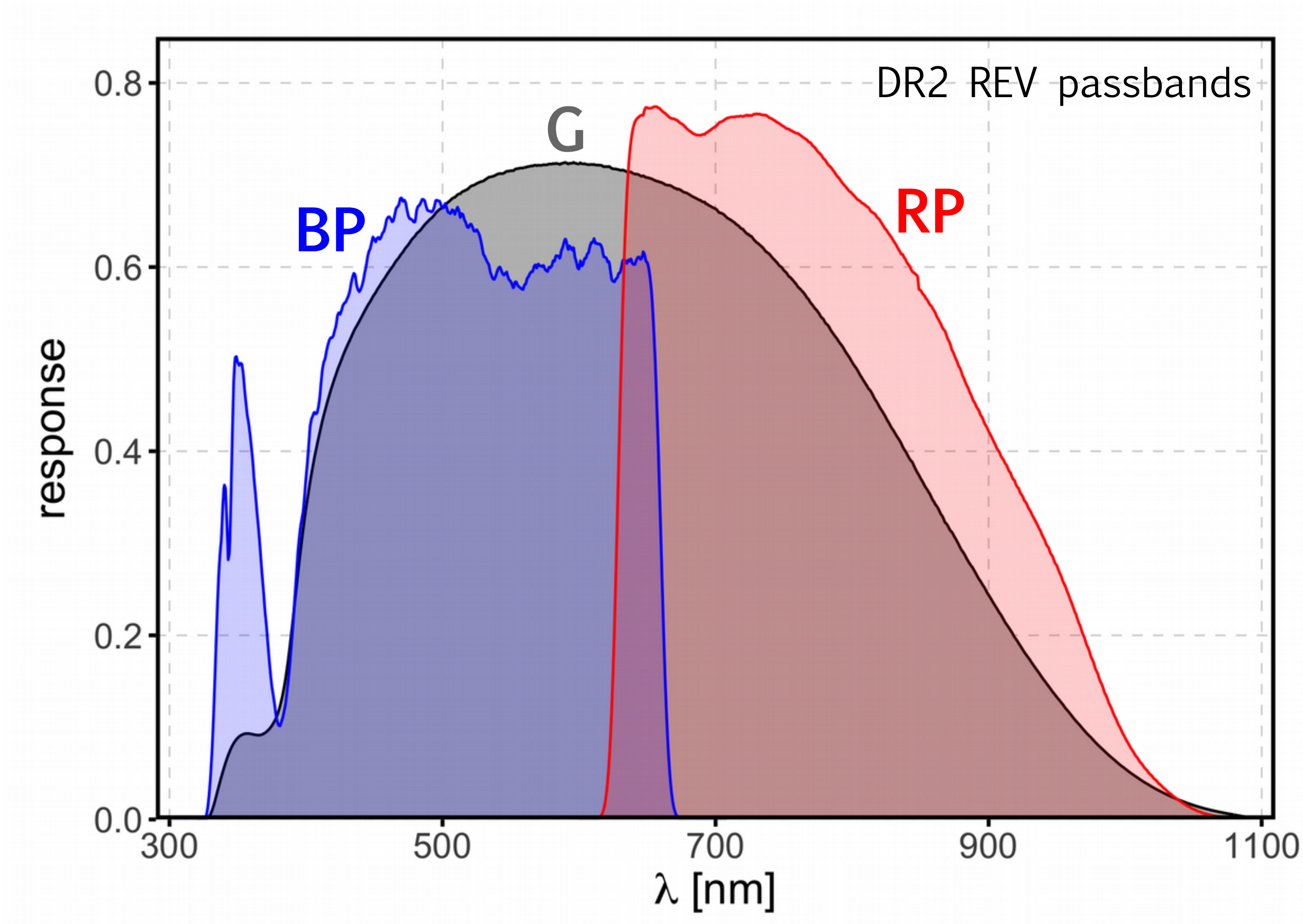
- ▷ for small M, polynomials worked out (Hipparcos, Tycho, *Gaia* DR1)
- ▷ cubic B-splines plus constant function worked out for *Gaia* DR2

Further refinements:

- ▷ allow for small variations in $\mathbf{p}$ within formal confidence region
- ▷ make $K > M$ to introduce free parameters in p

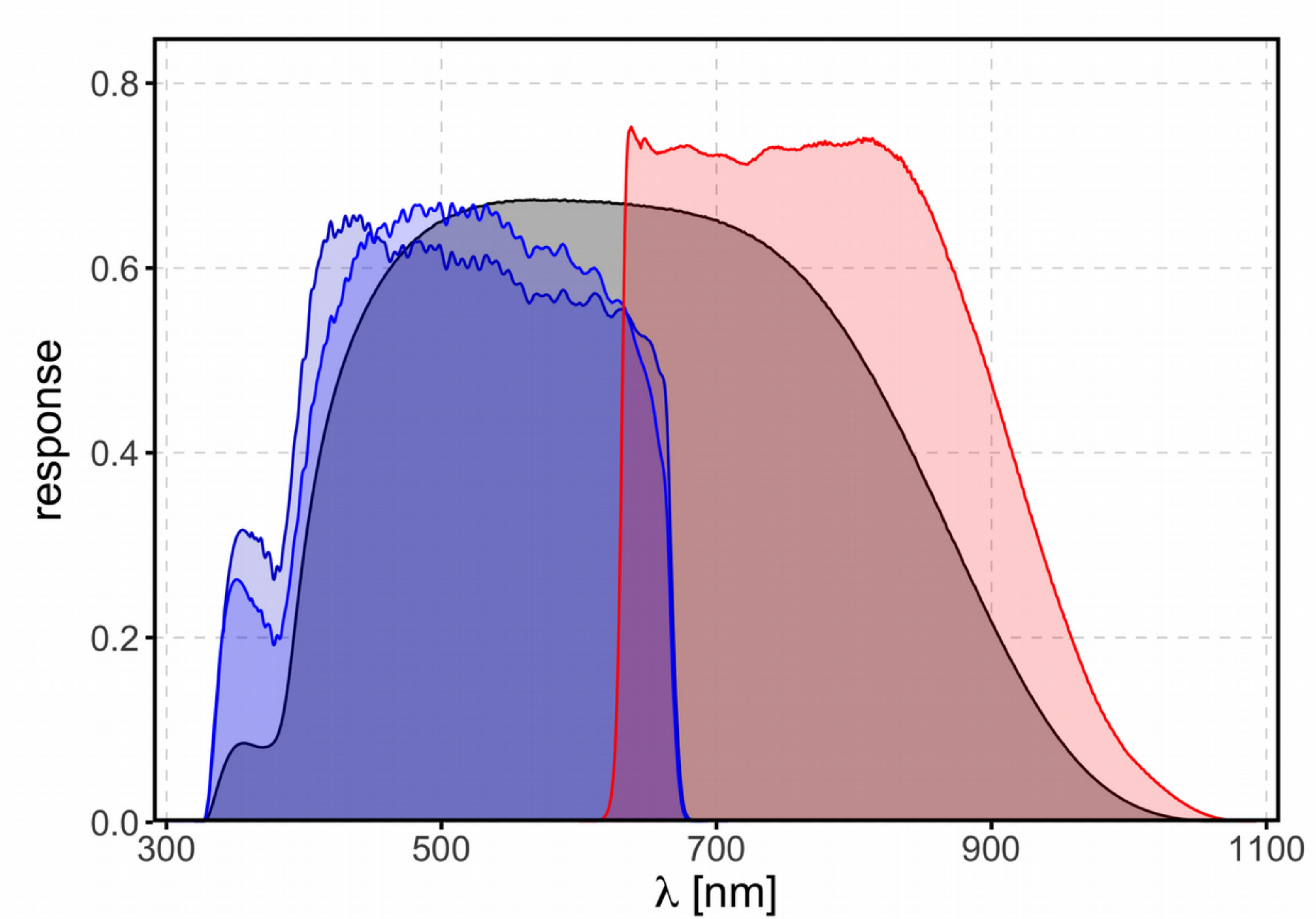
Gaia DR2 passbands: REV set

Set of passbands for G, BP, and RP provided with DR2 (Evans et al. 2018):

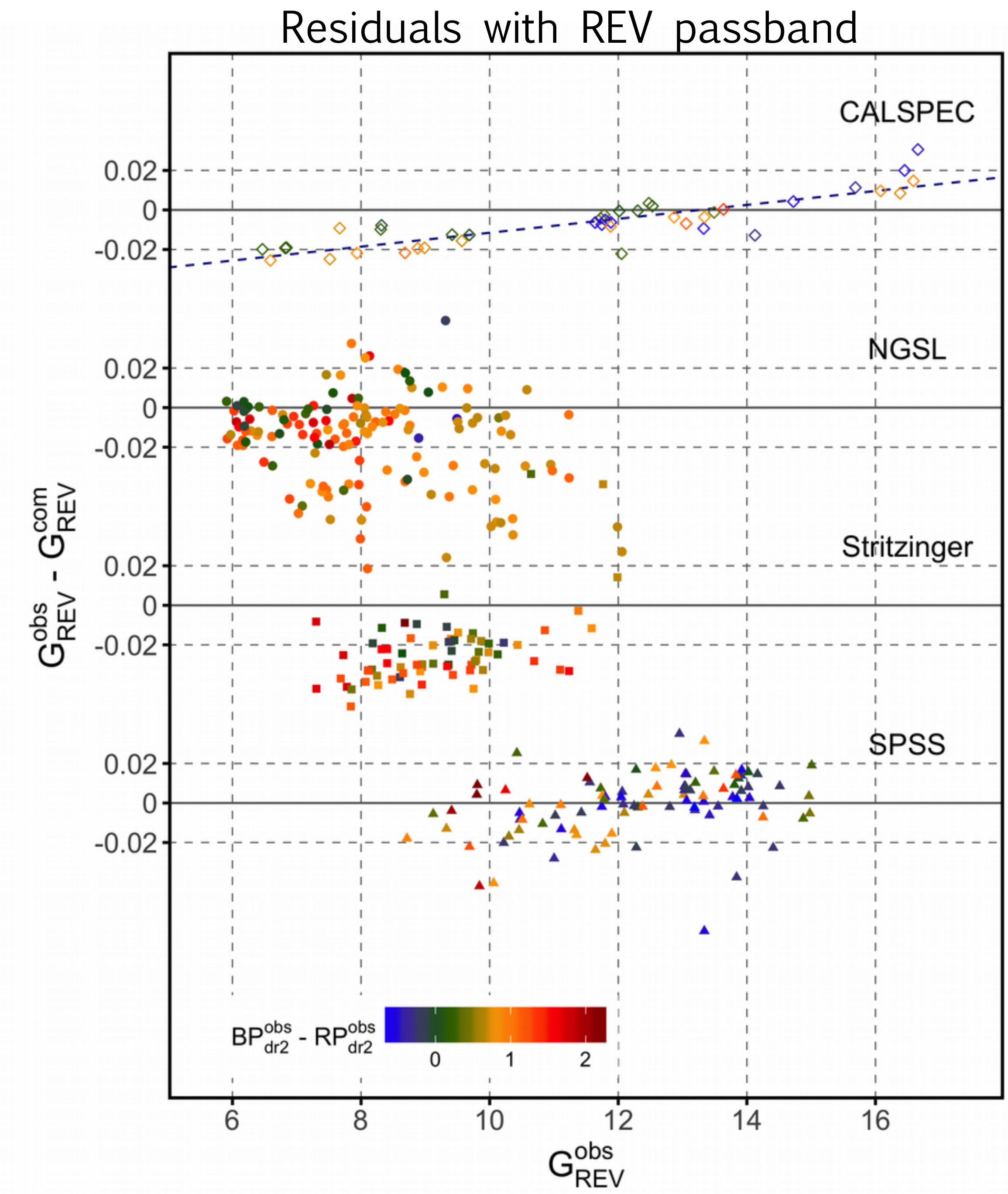


Gaia DR2 passbands: A new set

Alternative set of passbands for G, BP, and RP (Weiler 2018):



Gaia DR2 passbands: G

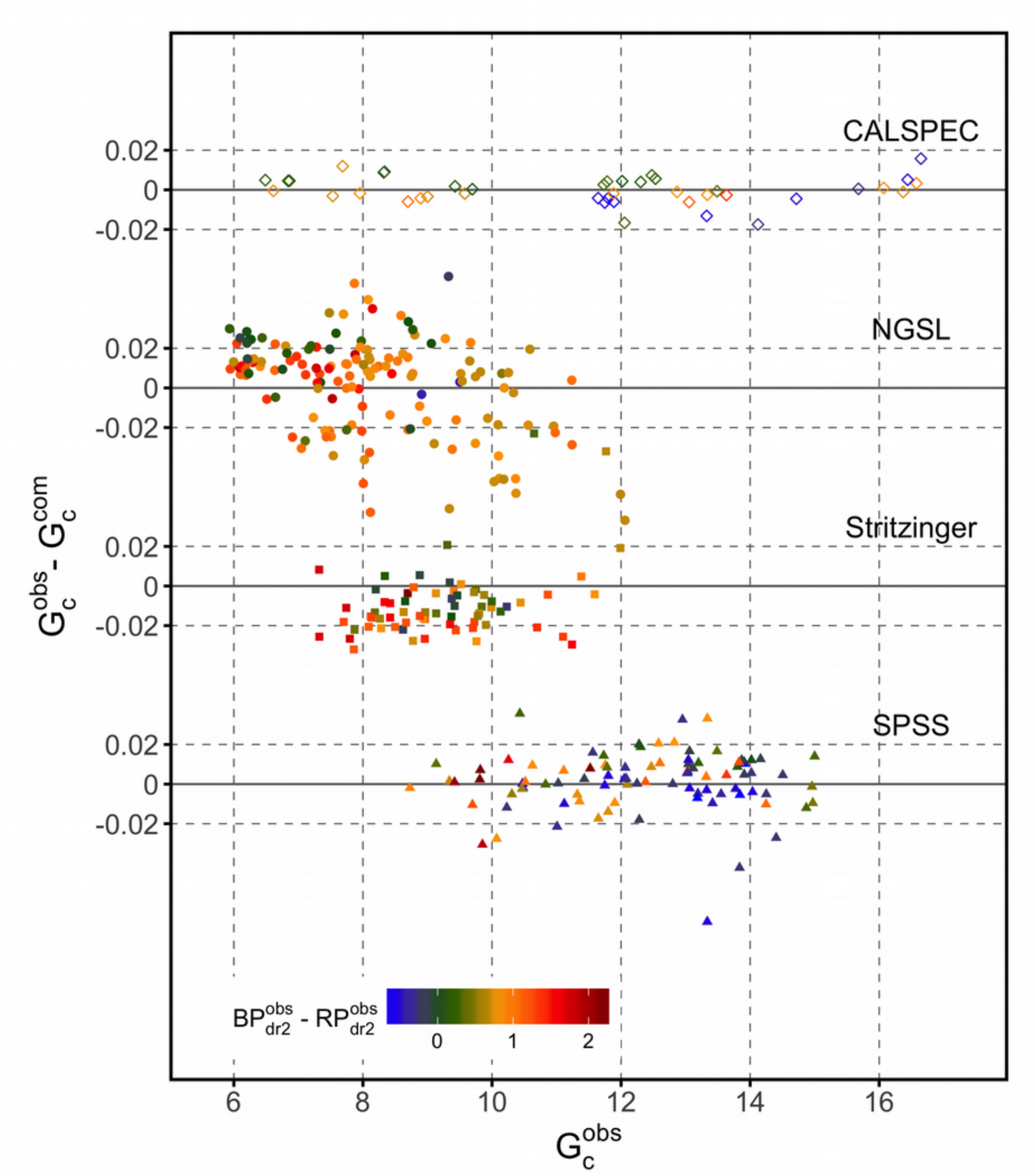


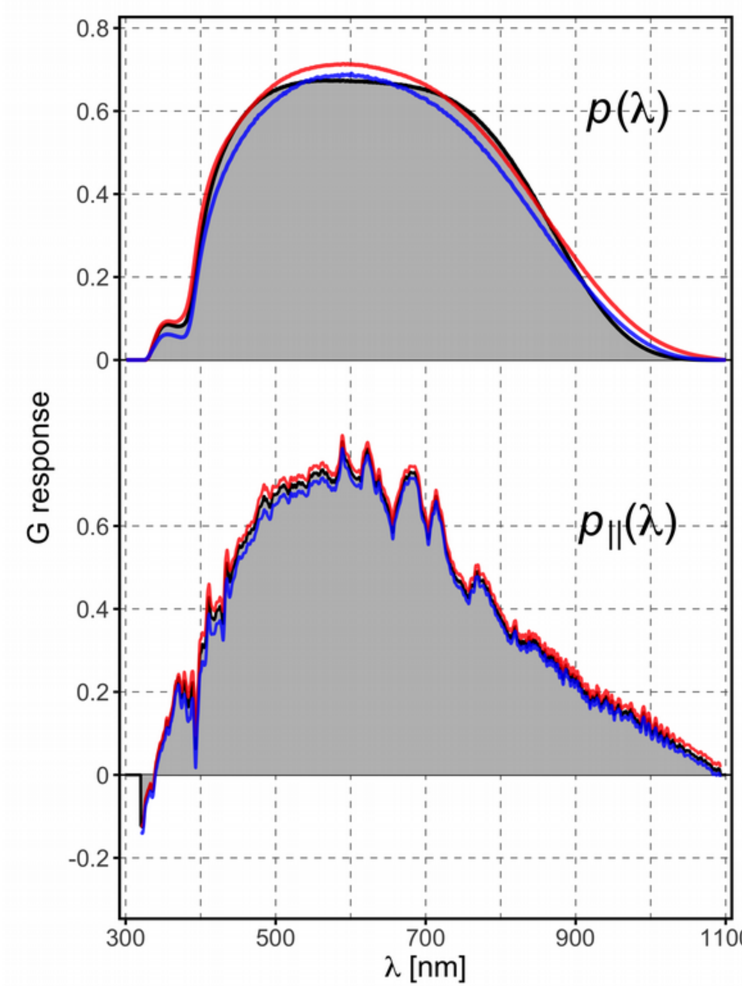
Trend with magnitude (cf. Evans et al. 2018, Arenou et al. 2018)

~ 3.5 mmag/mag – remove:

$$G_c = -0.9965 \cdot 2.5 \cdot \log_{10}(I_G) + zp$$

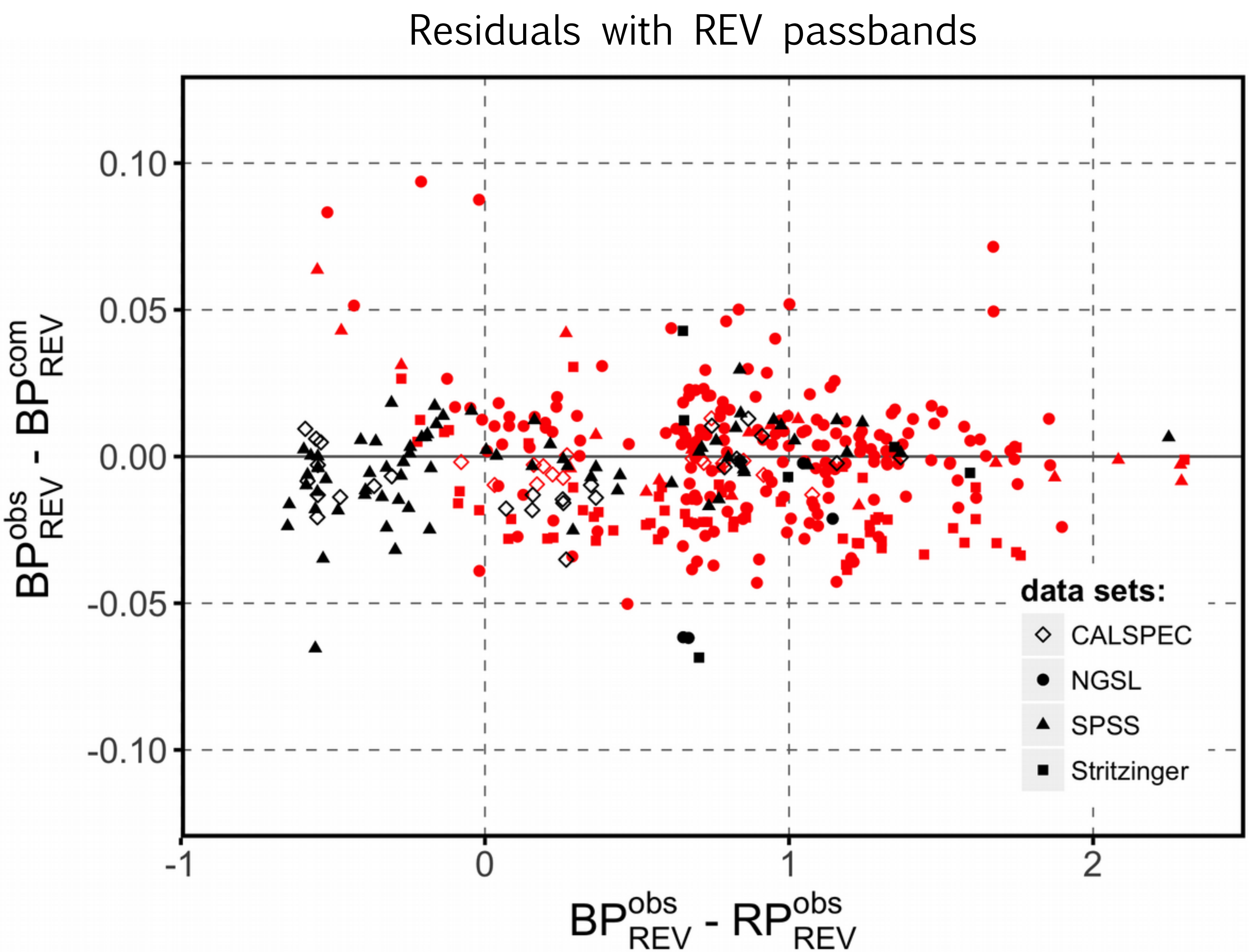
Gaia DR2 passbands: G





G passband essentially in agreement with pre-launch expectations.

Gaia DR2 passbands: BP



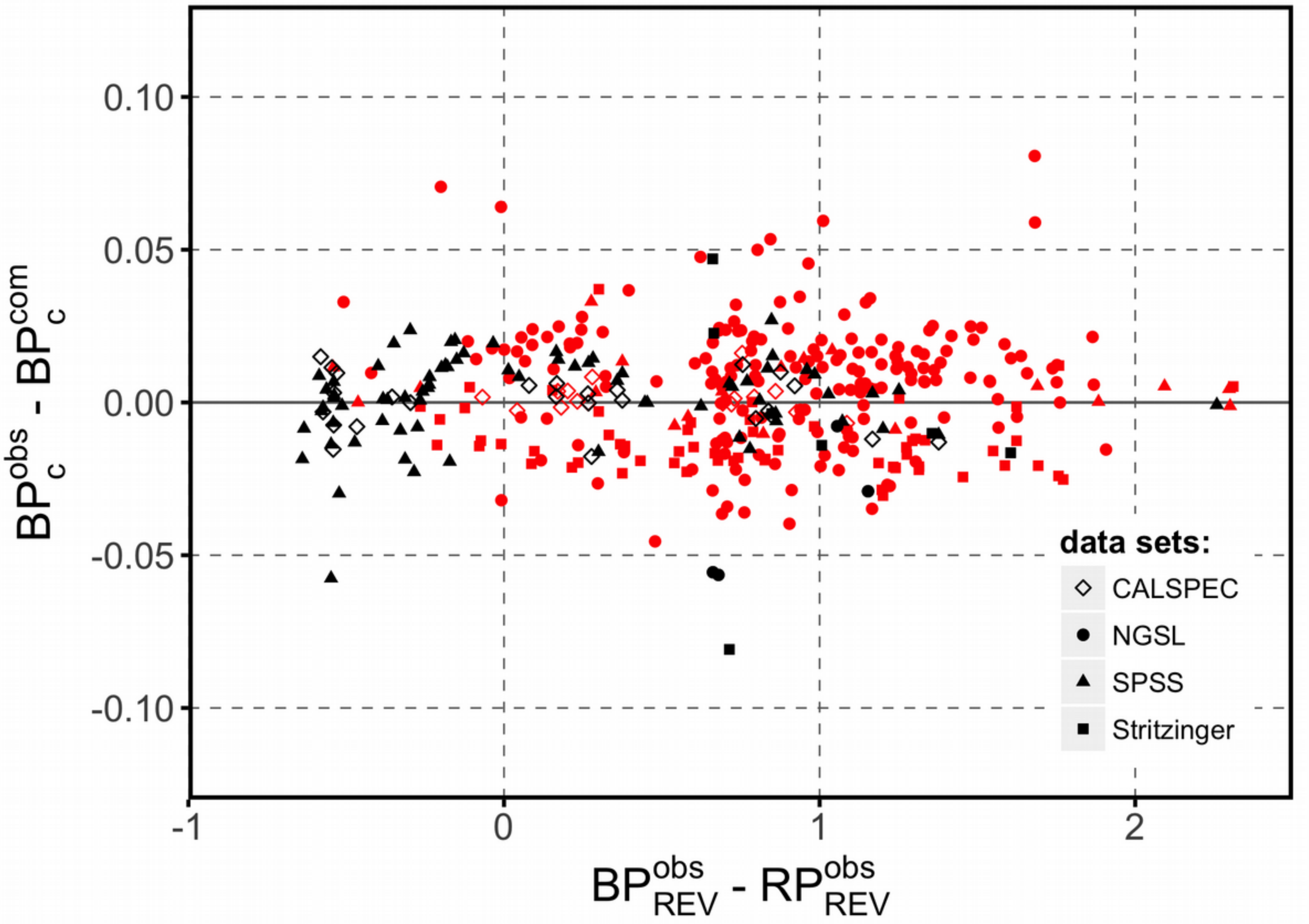
red:
G < 10.99

black:
G > 10.99

> Branching for blue sources at G ~ 10.99 *(cf. Arenou et al. 2018)*

➡ Deriving 2 passbands, for G < 10.99 and G > 10.99

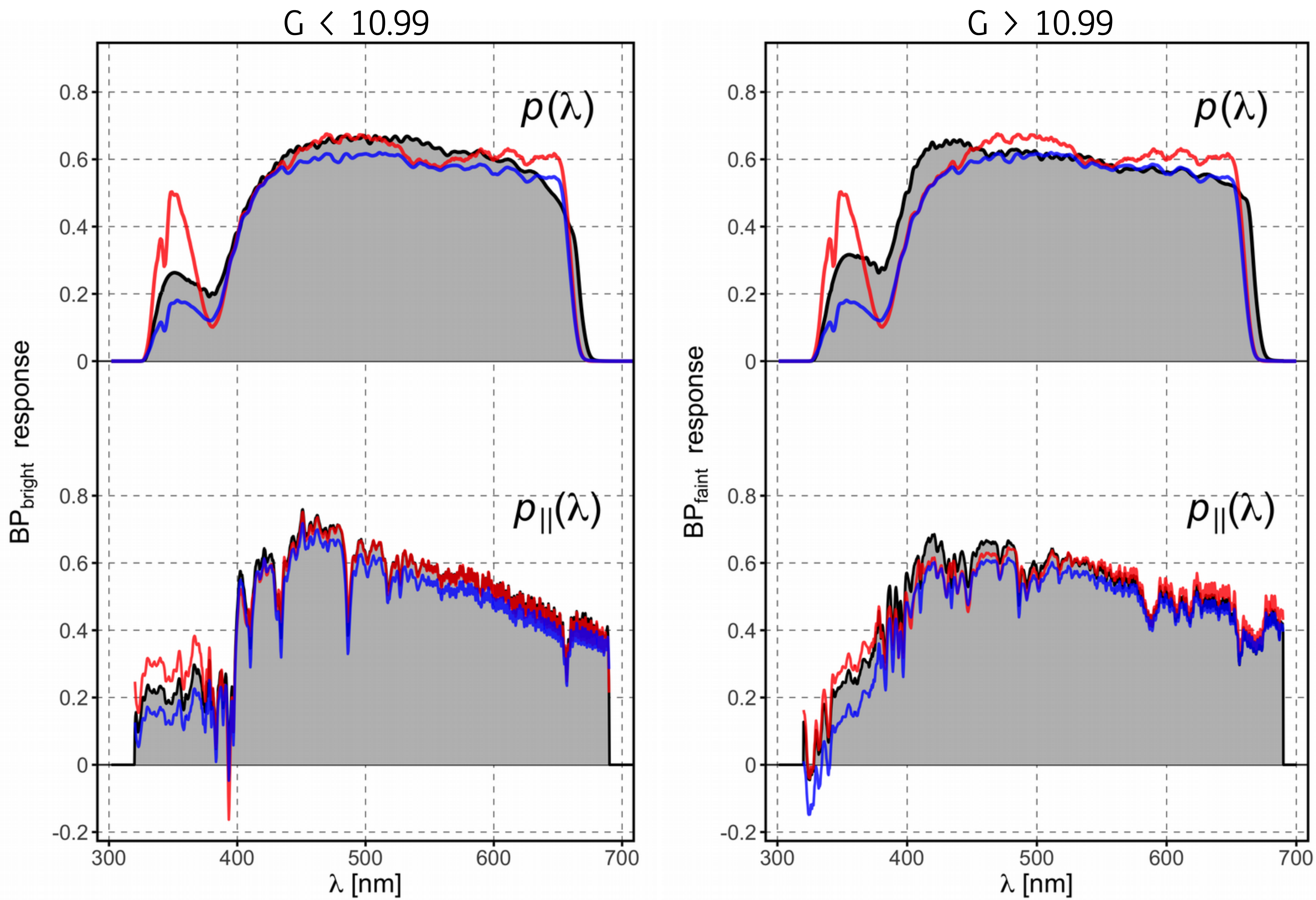
Gaia DR2 passbands: BP



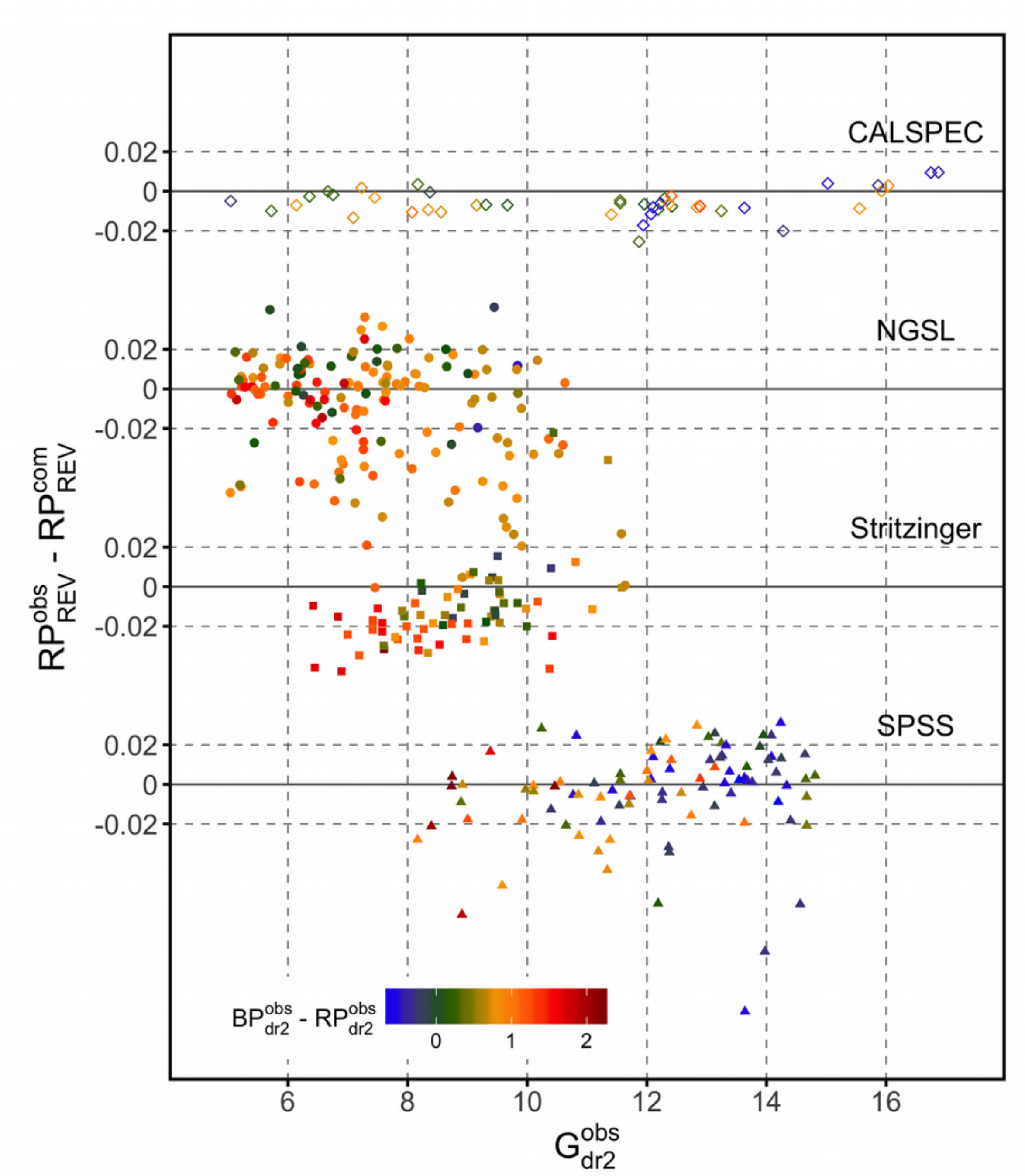
red:
G < 10.99

black:
G > 10.99

Gaia DR2 passbands: BP

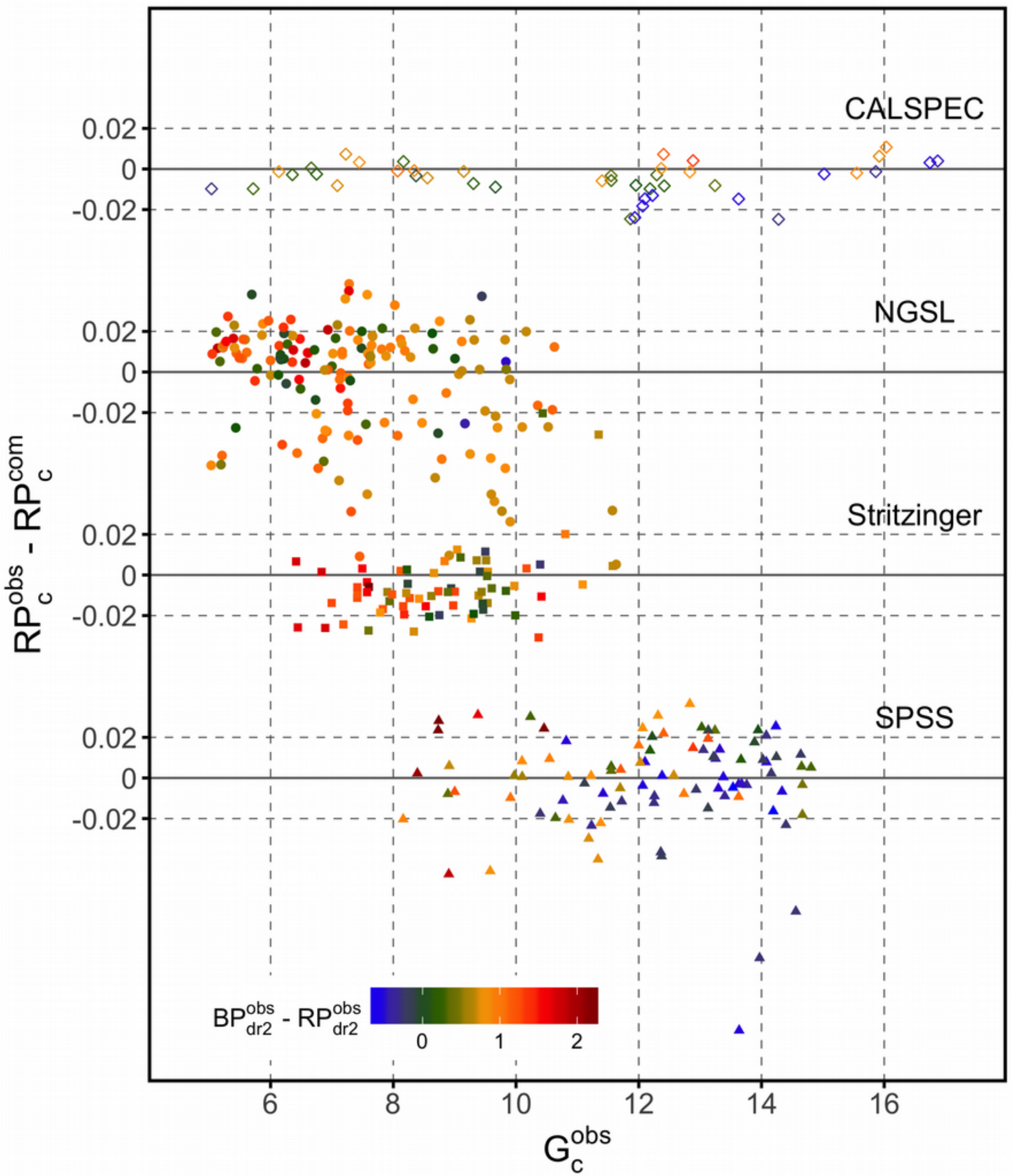


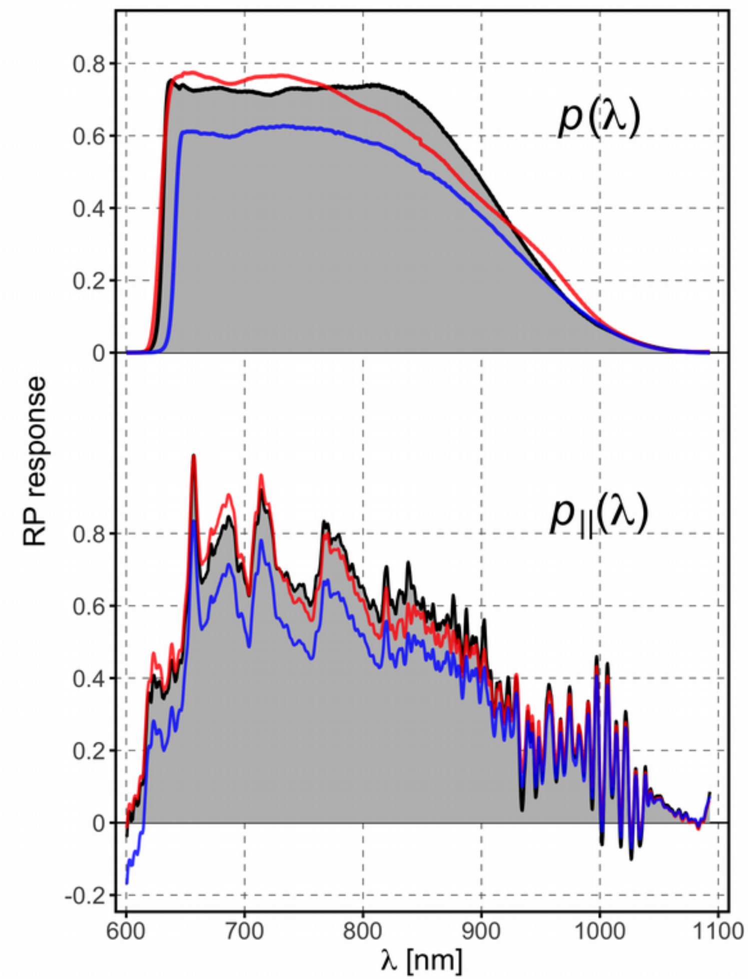
Gaia DR2 passbands: RP



Slight tendency for red sources (in particular SPSS and Stritzinger)

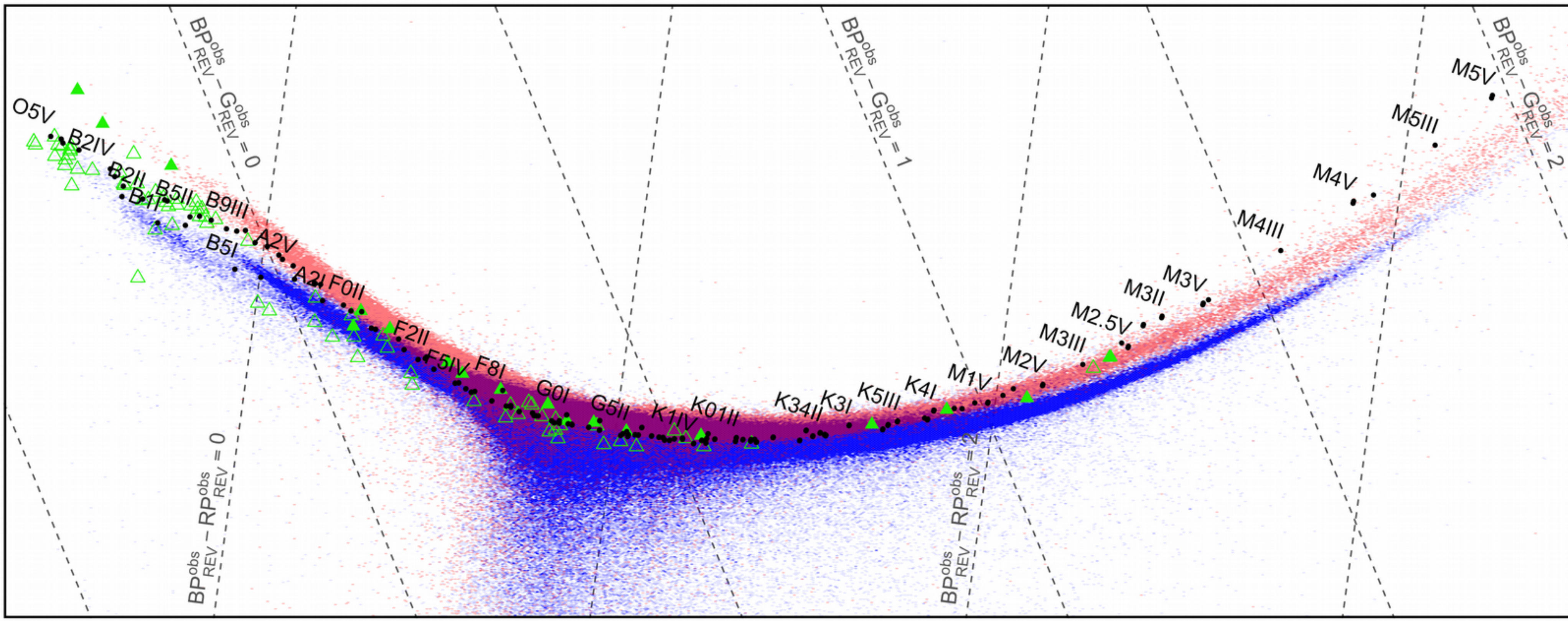
Gaia DR2 passbands: RP





Gaia DR2 passbands: colour-colour relations

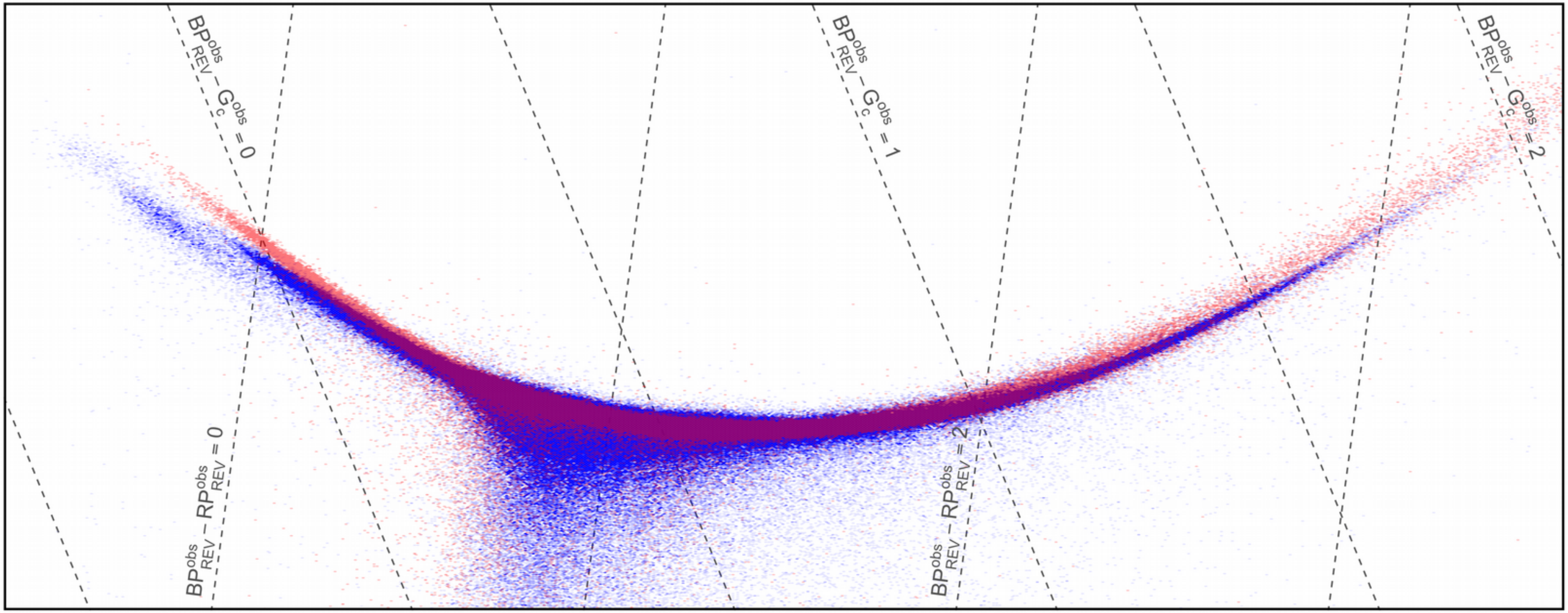
BP-RP vs. BP-G for $|b| > 30°$, BP < 17, RP < 17
REV passband



Red: G < 10.99 Green triangles: SPSS (calibration spectra)
Blue: G > 10.99 black dots: Pickles spectra

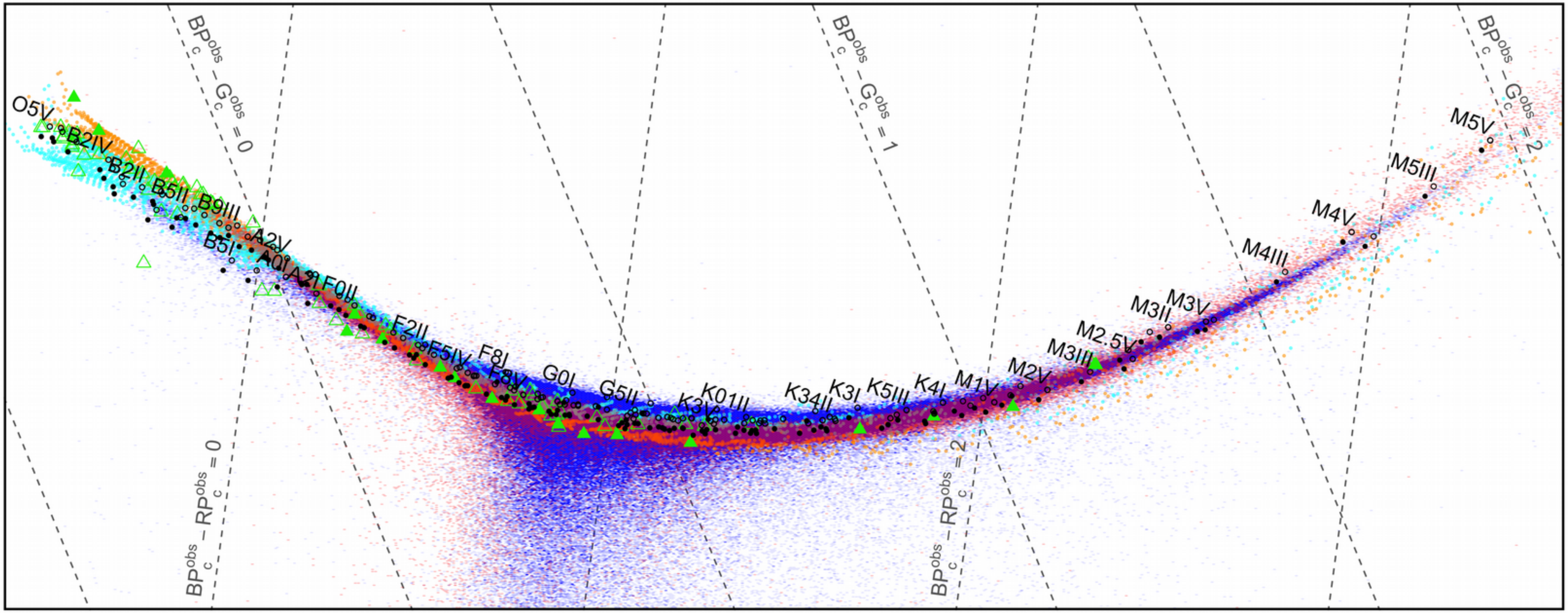
Gaia DR2 passbands: colour-colour relations

BP-RP vs. BP-G for $|b| > 30^{\circ}$, BP >17, RP > 17
G corrected *(essentially taking out 3.5 mmag/mag drift)*



Gaia DR2 passbands: colour-colour relations

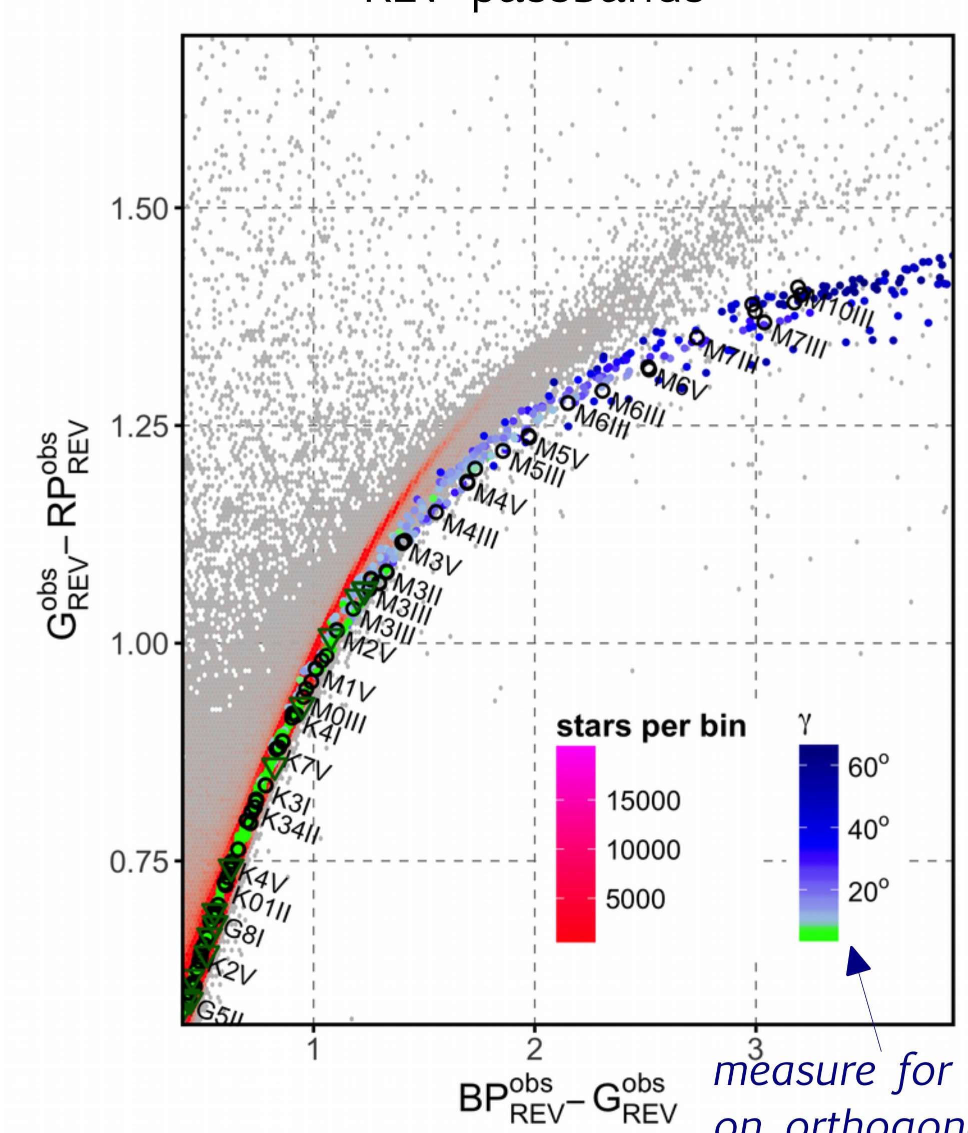
BP-RP vs. BP-G for $|b| > 30^{\circ}$, BP >17, RP > 17
All passbands corrected (Weiler 2018)



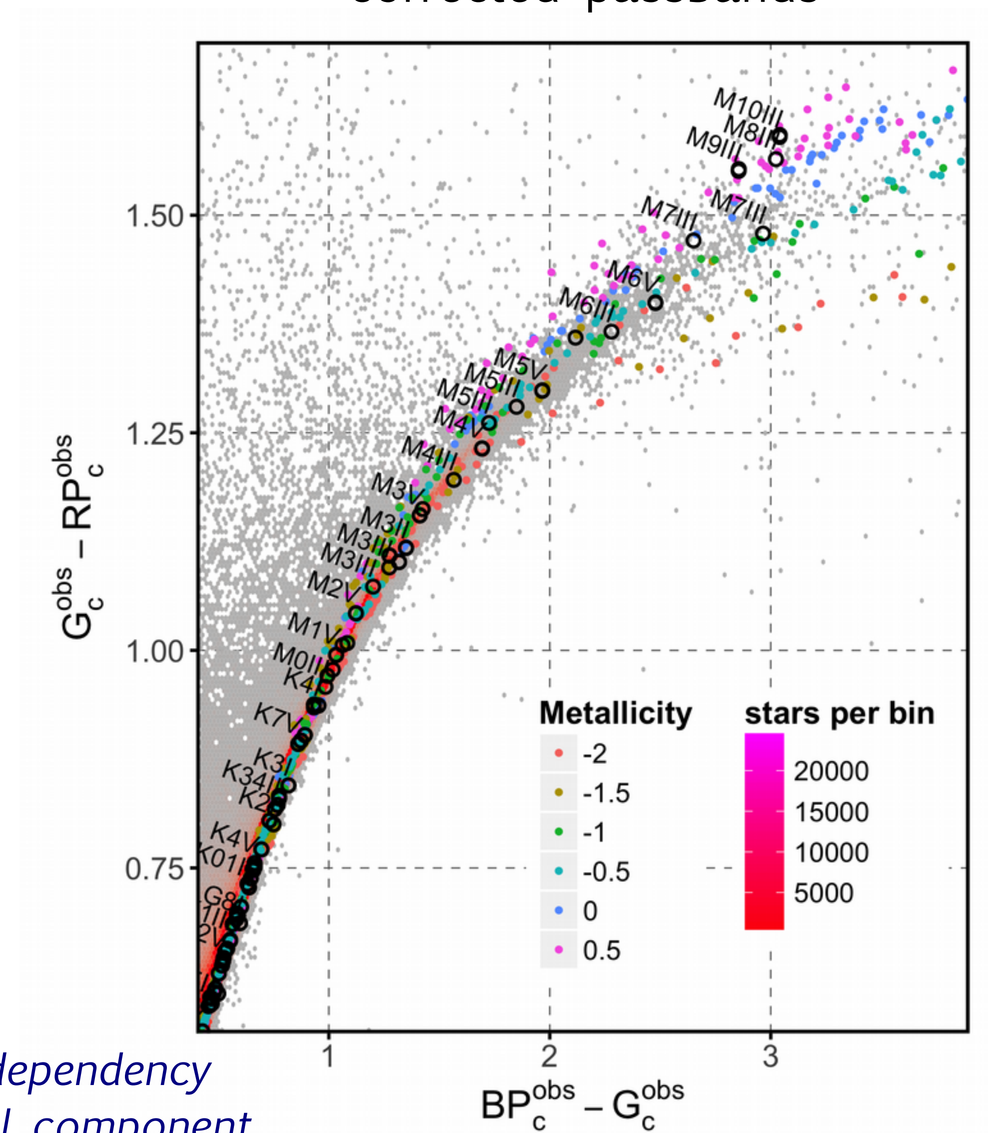
Gaia DR2 passbands: colour-colour relations

BP-G vs. G-RP for $|b| > 30°$, BP < 17, RP < 17

REV passbands



corrected passbands



measure for dependency on orthogonal component

Open symbols: Pickles spectra

filled symbols: BaSeL spectra

Summary

- Passbands are not uniquely defined by photometry of calibration spectra
- Reliable synthetic photometry is only possible for spectra that are a linear combination of the calibration spectra
- *Gaia* DR2 photometry shows systematic effects (3.5 mmag/mag drift in G, inconsistency in BP at G ~ 10.99 mag
- Official *Gaia* DR2 passbands are not optimal: Improved passbands available

For more information see:

Weiler et al. (2018), A&A, Forthcoming article *(on principles of passband reconstruction)*
https://arxiv.org/abs/1802.01667

Weiler (2018), A&A, submitted article *(on Gaia DR2 passbands)*
https://arxiv.org/abs/1805.08082