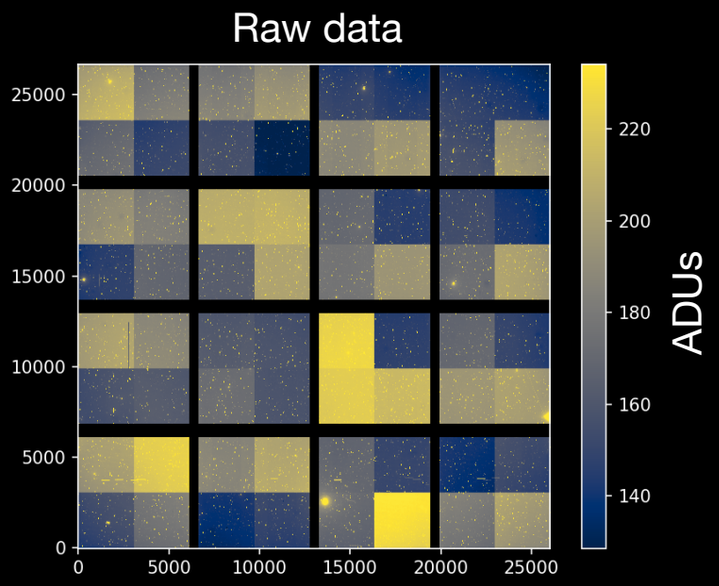
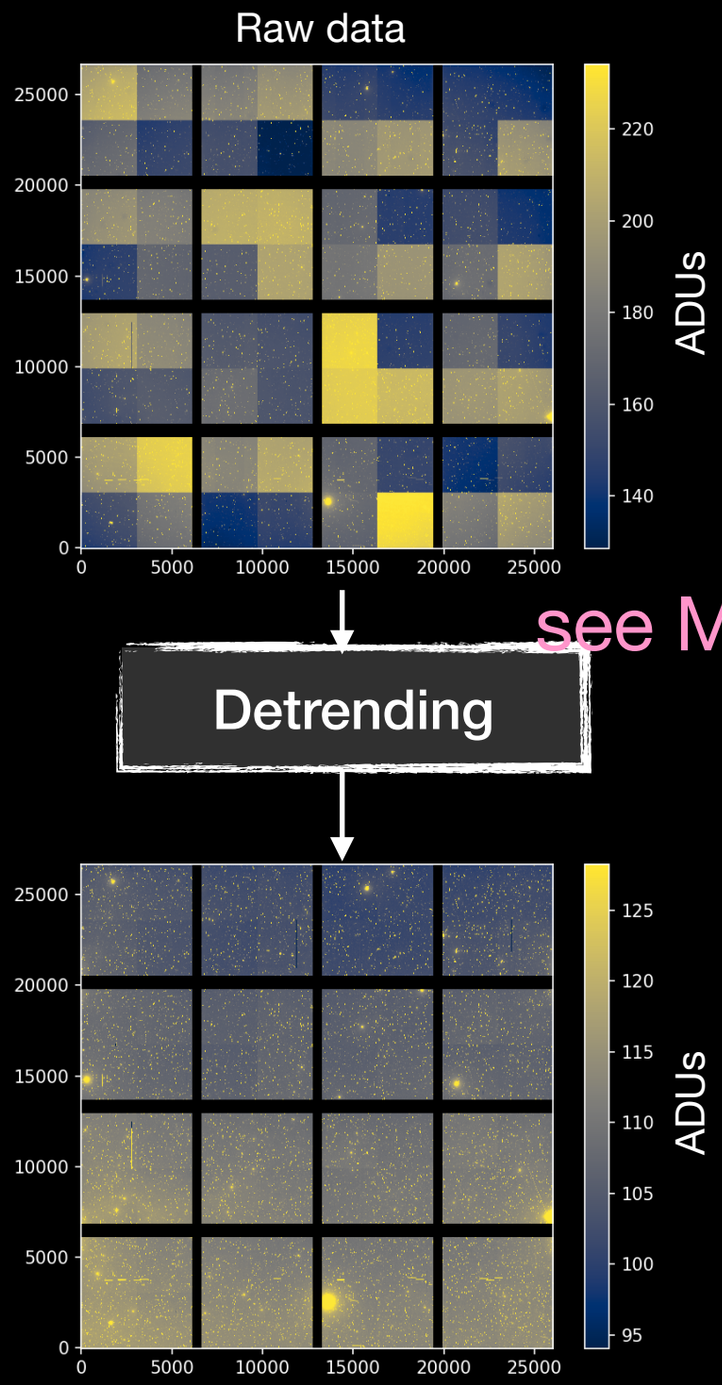
Ubercal

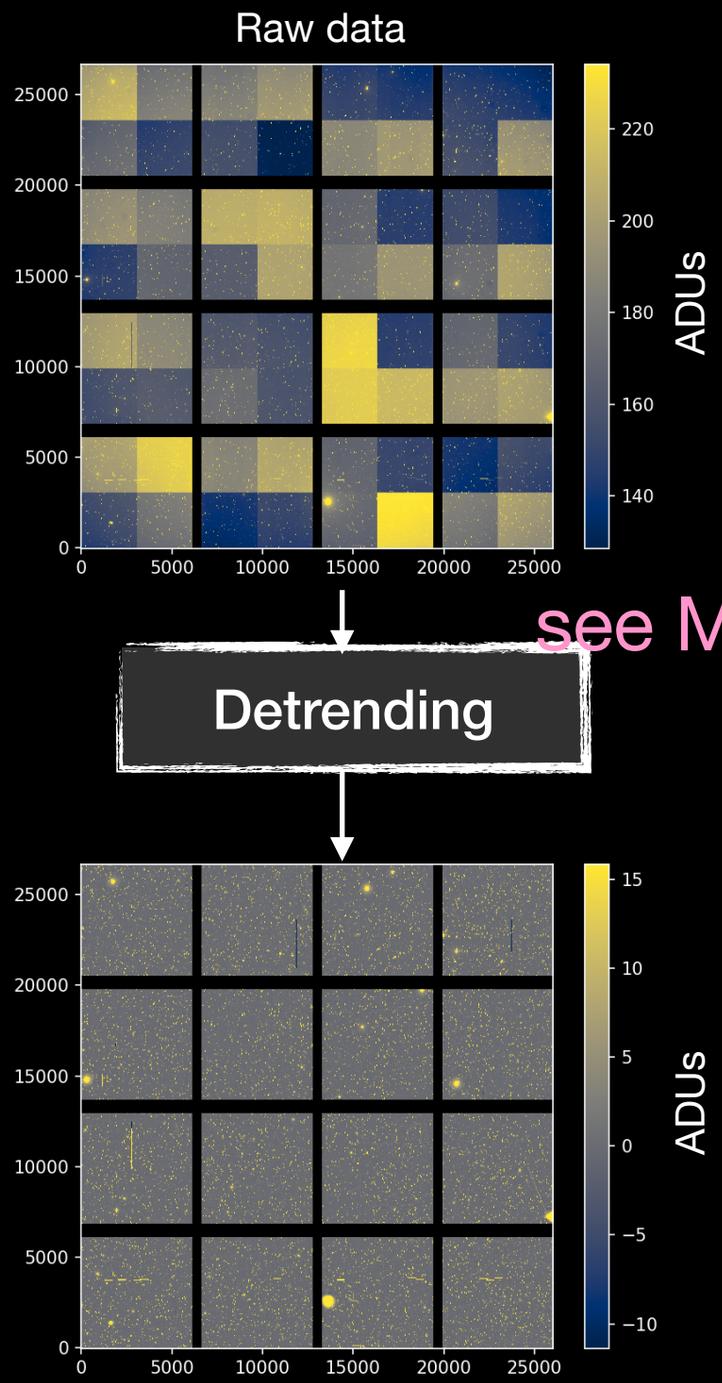
Paris, 28/09/26


Raw data
25000
20000
15000
10000
5000
0
0
5000
10000
15000
20000
25000
220
200
180
160
140
ADUs



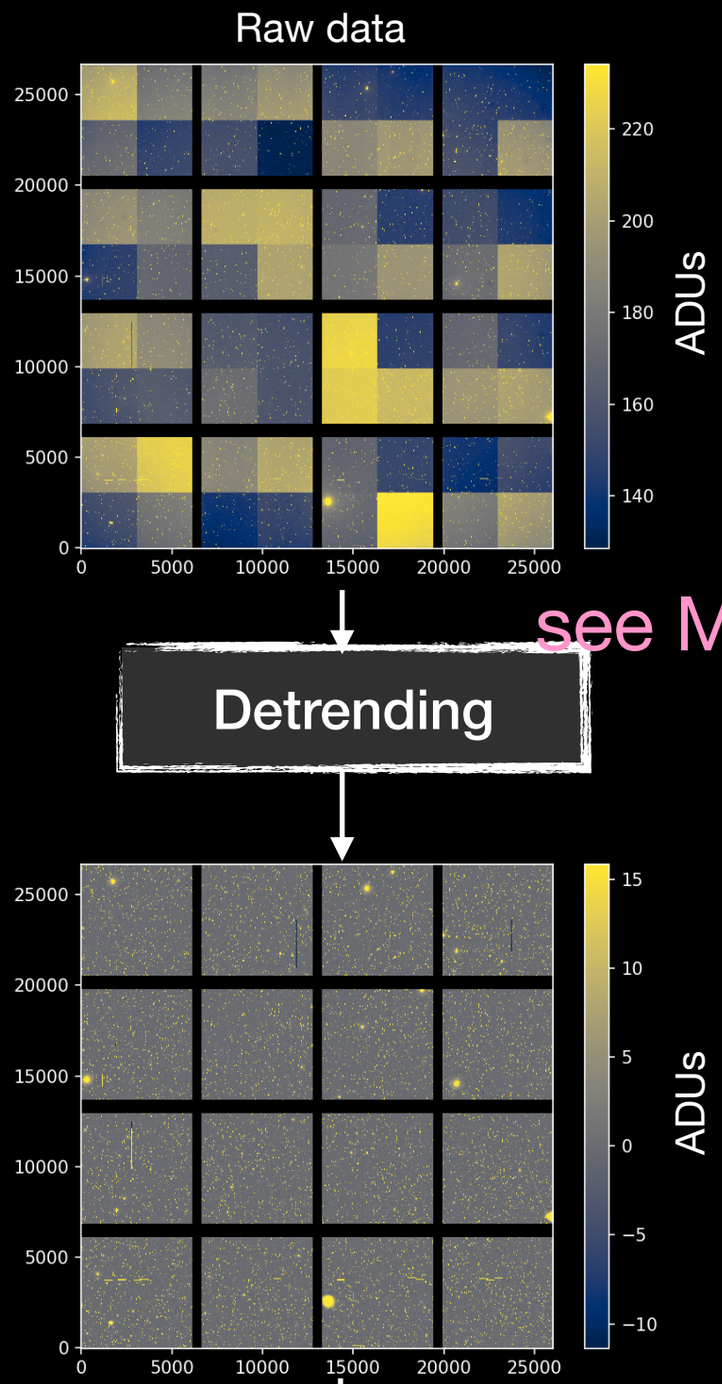
see Marie's talk

Detrending



see Marie’s talk

Detrending

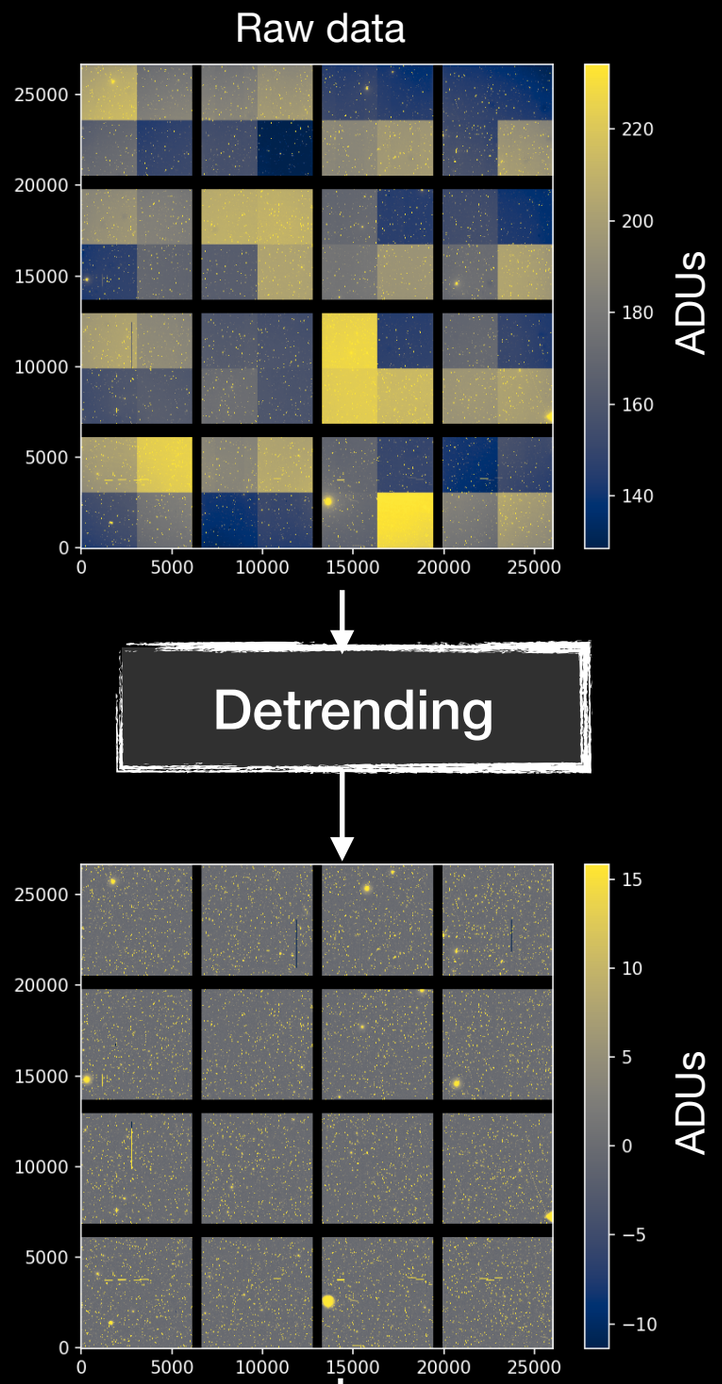


see Marie's talk

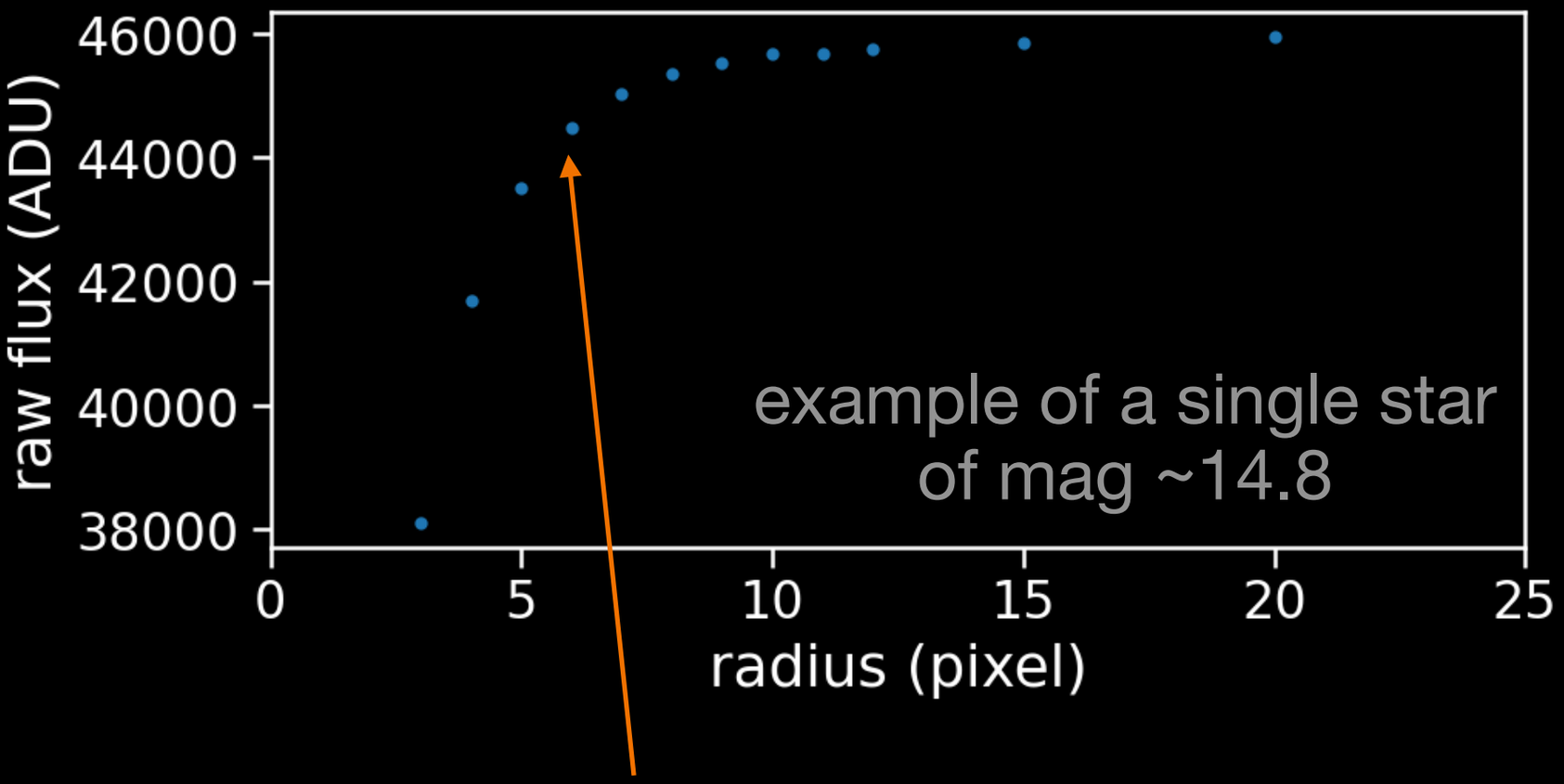
Detrending

Aperture photometry

Catalogs



We get the aperture photometry flux
in ADU
for every gaia star
for multiple radii



We use a radius of 6 pixels

Ubercal parametric model

$$m_{obs} = m_{star} + ZP(t_{exposure})$$

Fast change from atmosphere
Slow change from mirror aging?



Our main output:
A calibrated catalog !

⚠️ We work in magnitudes: $m_{obs} = -2.5 \log_{10}(f_{\mathrm{AP}})$

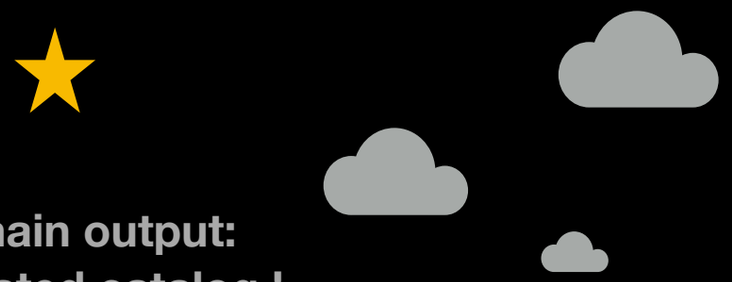
Ubercal parametric model

extinction

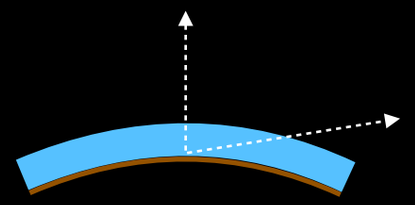
$$m_{obs} = m_{star} + ZP(t_{exposure}) + k(t_{night}) * \text{airmass}$$

Fast change from atmosphere
Slow change from mirror aging?

Low elevation
=
Observing through high airmass



Our main output:
A calibrated catalog !



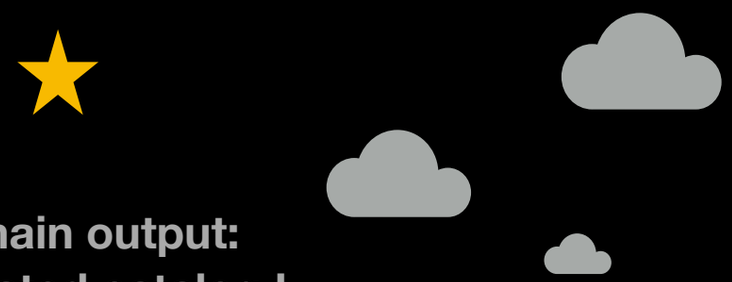
⚠️ We work in magnitudes: $m_{obs} = -2.5 \log_{10}(f_{\mathrm{AP}})$

Ubercal parametric model

extinction

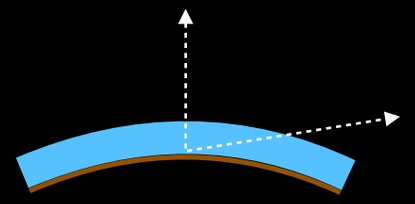
$$m_{obs} = m_{star} + ZP(t_{exposure}) + k(t_{night}) * \text{airmass} + \delta ZP(u, v)$$

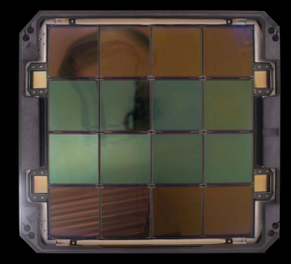
Fast change from atmosphere
Slow change from mirror aging?



Our main output:
A calibrated catalog !

Low elevation
=
Observing through
high airmass





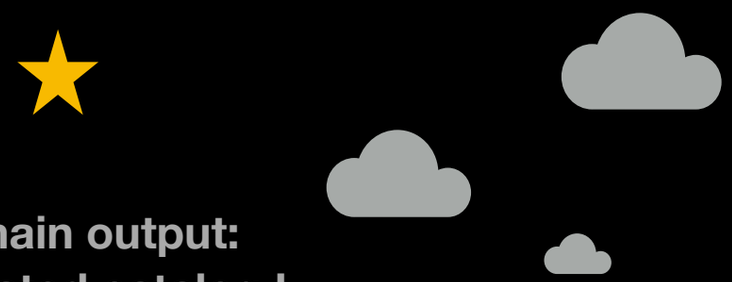
Gain variability
CCD width variation
Dust spots
Fringing
Laser annealing
...

⚠️ We work in magnitudes: $m_{obs} = -2.5 \log_{10}(f_{\mathrm{AP}})$

Ubercal parametric model

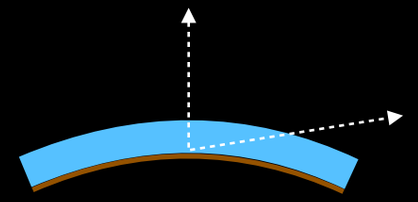
$$m_{obs} = m_{star} + ZP(t_{exposure}) + k(t_{night}) * \text{airmass} + \delta ZP(u, v)$$

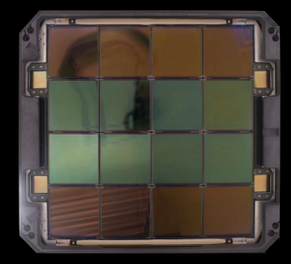
Fast change from atmosphere
Slow change from mirror aging?



Our main output:
A calibrated catalog !

Low elevation
=
Observing through
high airmass





Gain variability
CCD width variation
Dust spots
Fringing
Laser annealing
...

We use PS1 as a prior and fit for color corrections

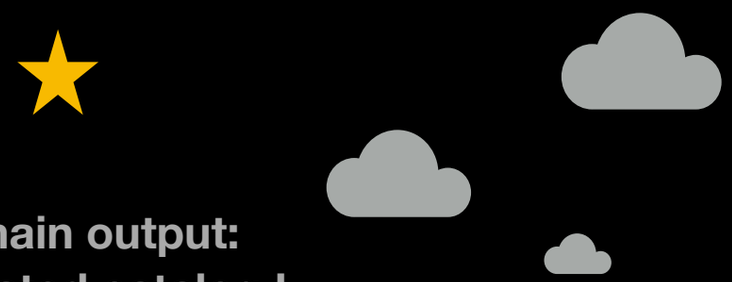
$$m_{\text{obs}} - m_{\text{PS}_1} = \text{ZP}(\text{t}_{\text{exp}}) + \text{k}(\text{t}_{\text{night}})\ \text{X} + \delta_{\text{ZP}}(\text{u}, \text{v}) + \alpha_{\text{c}}(\text{det})\ \text{c} + \text{noise}$$

~~Ubercal~~ parametric model

rename?

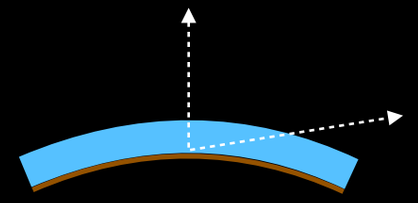
$$m_{obs} = m_{star} + ZP(t_{exposure}) + k(t_{night}) * \text{airmass} + \delta ZP(u, v)$$

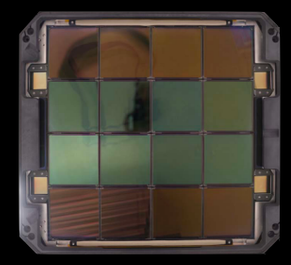
Fast change from atmosphere
Slow change from mirror aging?



Our main output:
A calibrated catalog !

Low elevation
=
Observing through
high airmass





Gain variability
CCD width variation
Dust spots
Fringing
Laser annealing
...

We use PS1 as a prior and fit for color corrections

$$m_{\text{obs}} - m_{\text{PS}_1} = \text{ZP}(\text{t}_{\text{exp}}) + \text{k}(\text{t}_{\text{night}})\ \text{X} + \delta_{\text{ZP}}(\text{u}, \text{v}) + \alpha_{\text{c}}(\text{det})\ \text{c} + \text{noise}$$

$$m_{\mathrm{obs}} - m_{\mathrm{PS}_1} = \mathrm{ZP}(\mathrm{t_{exp}}) + \mathrm{k}(\mathrm{t_{night}})\ \mathrm{X} + \delta_{\mathrm{ZP}}(\mathrm{u, v}) + \alpha_{\mathrm{c}}(\mathrm{det})\ \mathrm{c} + \mathrm{noise}$$

$$m_{\mathrm{obs}} - m_{\mathrm{PS_1}} = \mathrm{ZP}(\mathrm{t_{exp}}) + \mathrm{k}(\mathrm{t_{night}})\ \mathrm{X} + \delta_{\mathrm{ZP}}(\mathrm{u}, \mathrm{v}) + \alpha_{\mathrm{c}}(\mathrm{det})\ \mathrm{c} + \mathrm{noise}$$

$$m_{\mathrm{obs}} - m_{\mathrm{PS_1}} = Ap + \mathrm{noise}$$

A is a $n_{\mathrm{obs}} \times n_{\mathrm{par}}$ matrix,

p is a parameter vector ($\mathrm{ZP}(\mathrm{t_{exp}})$, $\mathrm{k}(\mathrm{t_{night}})$, $\delta_{\mathrm{ZP}}(\mathrm{u}, \mathrm{v})$, $\alpha_{\mathrm{c}}(\mathrm{det})$)

$$\mathbf{A}^T C^{-1} \mathbf{A} p = \mathbf{A}^T C^{-1} (m_{\mathrm{obs}} - m_{\mathrm{PS_1}})$$

$$m_{\mathrm{obs}} - m_{\mathrm{PS_1}} = \mathrm{ZP}(\mathrm{t_{exp}}) + \mathrm{k}(\mathrm{t_{night}})\ \mathrm{X} + \delta_{\mathrm{ZP}}(\mathrm{u}, \mathrm{v}) + \alpha_{\mathrm{c}}(\mathrm{det})\ \mathrm{c} + \mathrm{noise}$$

$$m_{\mathrm{obs}} - m_{\mathrm{PS_1}} = Ap + \mathrm{noise}$$

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p is a parameter vector ($\mathrm{ZP}(\mathrm{t_{exp}})$, $\mathrm{k}(\mathrm{t_{night}})$, $\delta_{\mathrm{ZP}}(\mathrm{u}, \mathrm{v})$, $\alpha_{\mathrm{c}}(\mathrm{det})$)

$$\mathbf{A}^T C^{-1} \mathbf{A} p = \mathbf{A}^T C^{-1} (m_{\mathrm{obs}} - m_{\mathrm{PS_1}})$$

We use sparse algorithm to solve these huge systems
Fitting on calibrators
isolated stars selected as main sequence + white dwarves using gaia colors and absolute magnitudes

We solve iteratively, removing bad data and bad stars and refining the model at every iterations (stop after 12 iterations)

$$m_{\mathrm{obs}} - m_{\mathrm{PS}_1} = \mathrm{ZP}(\mathrm{t_{exp}}) + \mathrm{k}(\mathrm{t_{night}})\ \mathrm{X} + \delta_{\mathrm{ZP}}(\mathrm{u}, \mathrm{v}) + \alpha_{\mathrm{c}}(\mathrm{det})\ \mathrm{c} + \mathrm{noise}$$

$$m_{\mathrm{obs}} - m_{\mathrm{PS}_1} = Ap + \mathrm{noise}$$

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$$\mathbf{A}^T C^{-1} \mathbf{A} p = \mathbf{A}^T C^{-1} (m_{\mathrm{obs}} - m_{\mathrm{PS}_1})$$

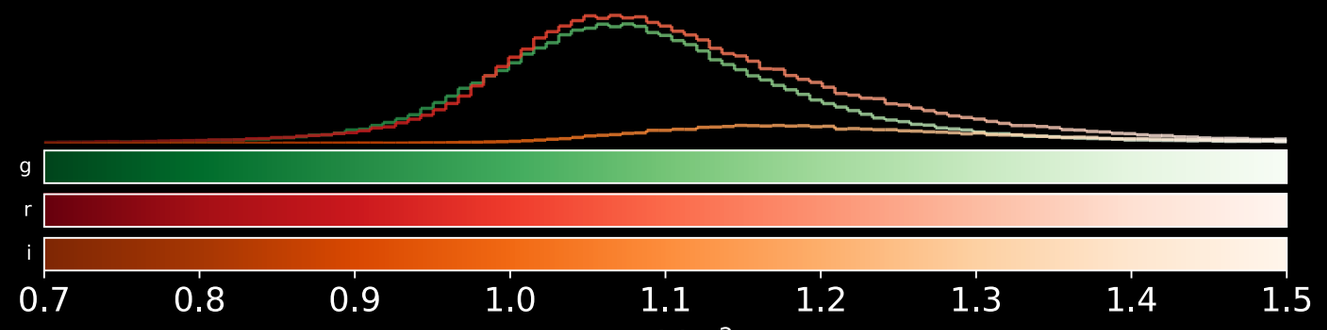
We use sparse algorithm to solve these huge systems
Fitting on calibrators
isolated stars selected as main sequence + white dwarves using gaia colors and absolute magnitudes

We solve iteratively, removing bad data and bad stars and refining the model at every iterations (stop after 12 iterations)

We fit per year per half sky
(could be changed to flat-field periods, see Marie's talk)

Fast change from atmosphere
Slow change from mirror aging?

$ZP(t_{exp})$



Zero Points

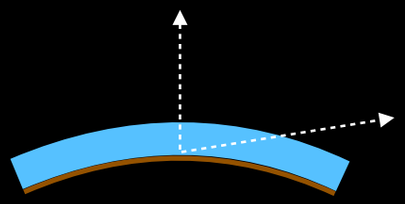


ZTF-g

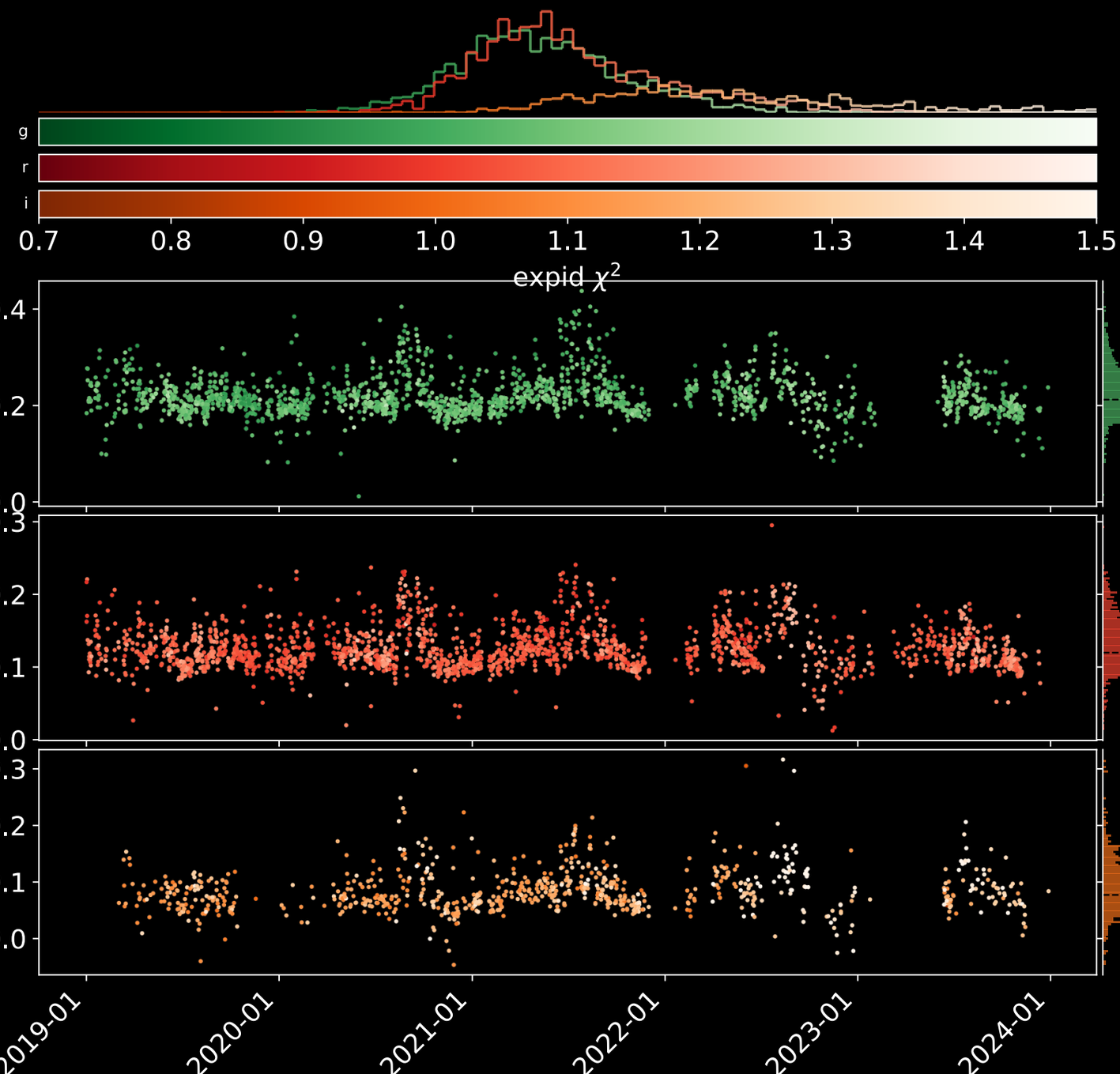
ZTF-r

ZTF-i

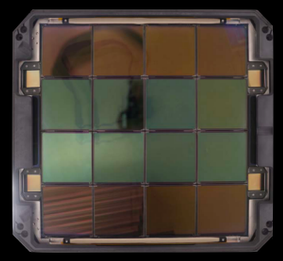
Low elevation
=
Observing through
high airmass



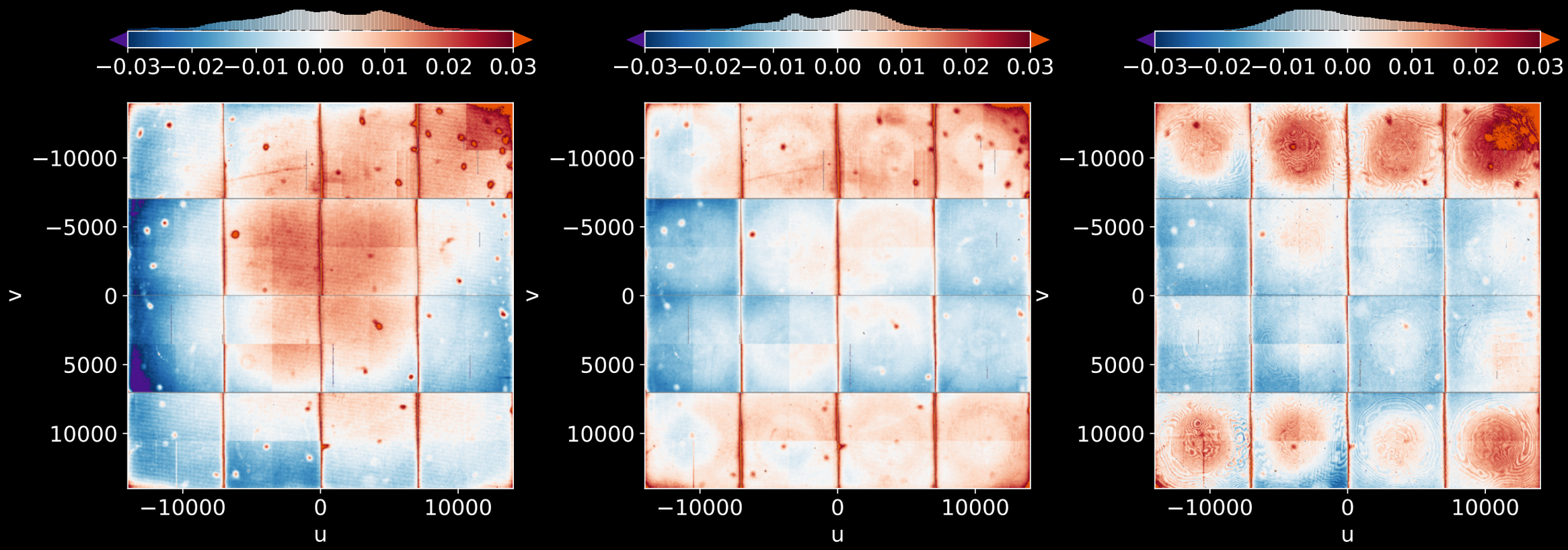
Extinction $k(t_{night})$



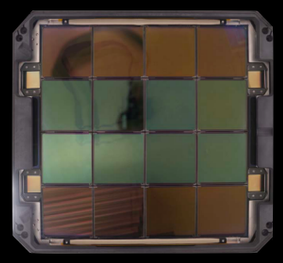
Uberflats $\delta_{ZP}(u, v)$



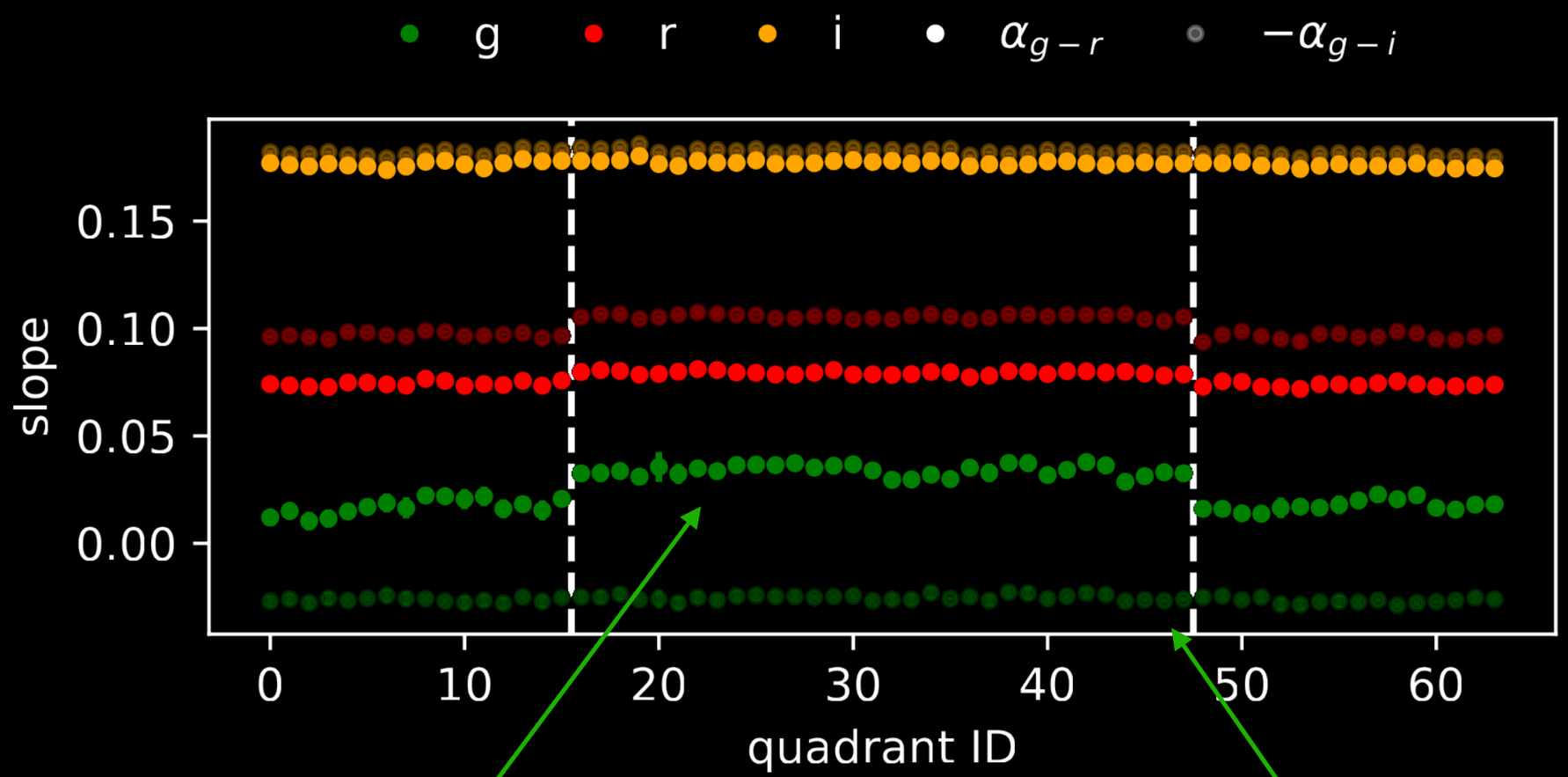
Gain variability
CCD width variation
Dust spots
Fringing
Laser annealing
...



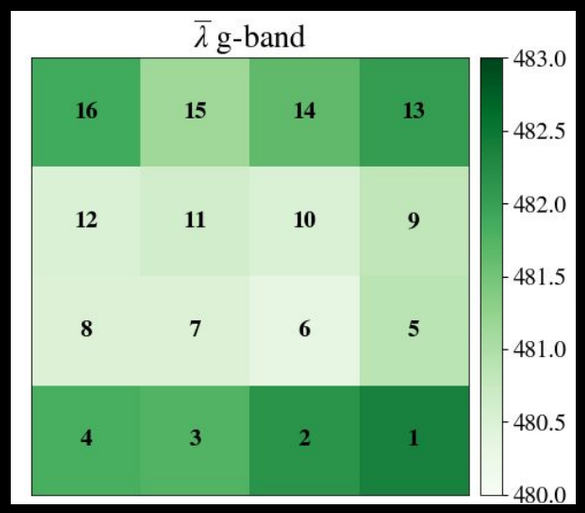
ZTF-g ZTF-r ZTF-i



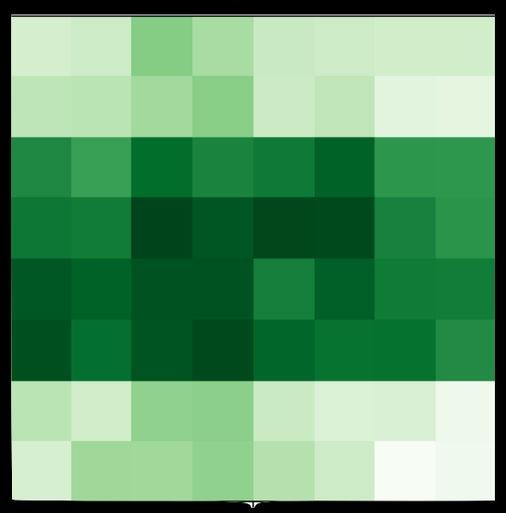
Color slopes α_c(quadrant)



band shift from Enya's talk



α_{g-r}



α_{g-i}



Repopulation

We go back to the whole aperture catalog in flux (not restricted to calibrators)

Repopulation

We go back to the whole aperture catalog in flux (not restricted to calibrators) and we calibrate

$$f = f_{\mathrm{AP}} \times 10^{-0.4\,\mathrm{ZP}_{\mathrm{tot}}}$$

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Note that we do not use color corrections here

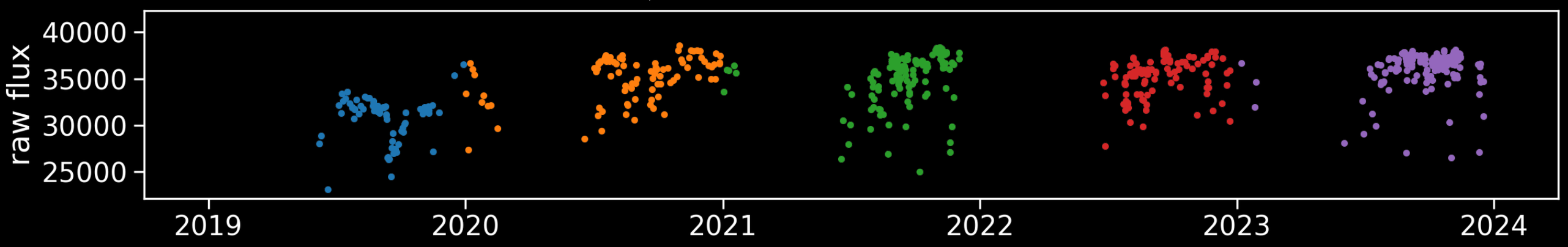
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Note that we do not use color corrections here



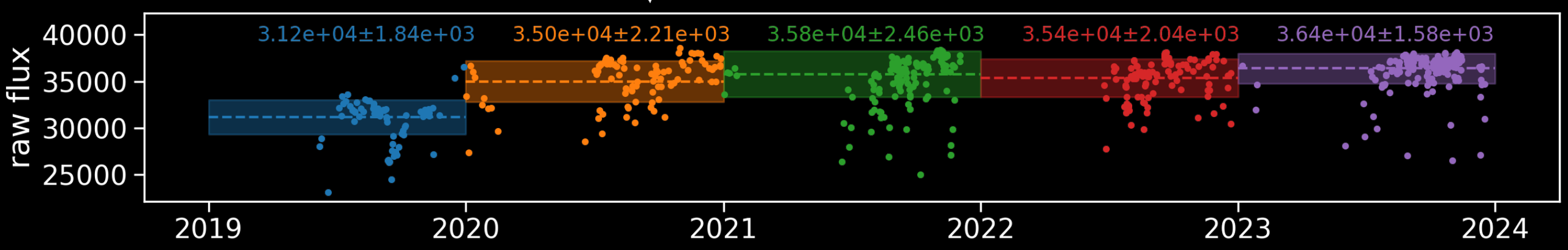
Repopulation

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Note that we do not use color corrections here



Before calibration: relative precision of ~10%

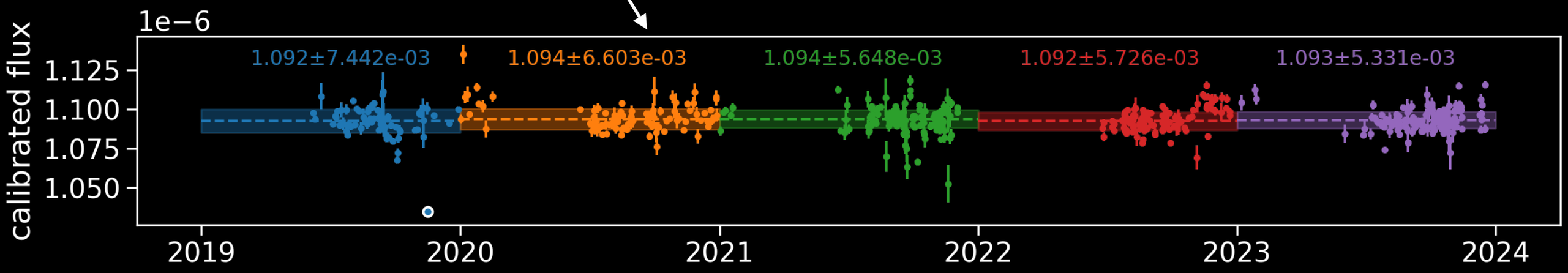
Repopulation

We go back to the whole aperture catalog in flux (not restricted to calibrators) and we calibrate

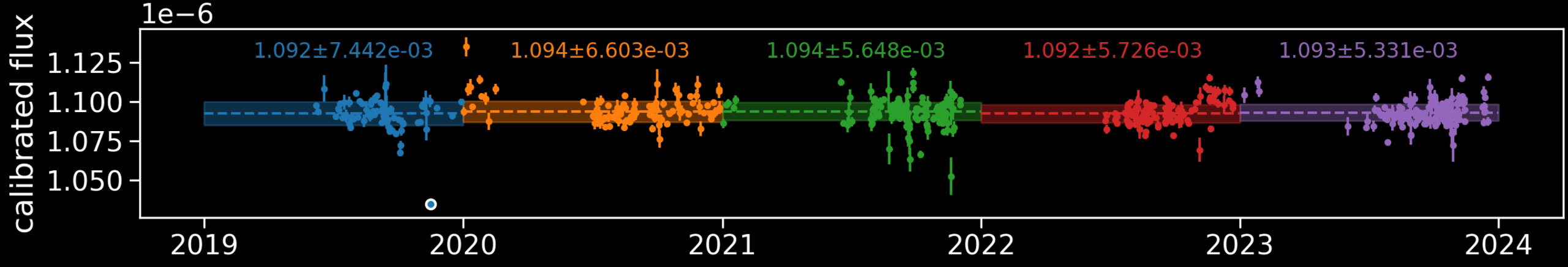
$$f = f_{\mathrm{AP}} \times 10^{-0.4\,\mathrm{ZP_{tot}}}$$

$$\mathrm{ZP_{tot}} = \mathrm{ZP}(\mathrm{t_{exp}}) + \mathrm{k}(\mathrm{t_{night}})\ \mathrm{X} + \delta_{\mathrm{ZP}}(\mathrm{u}, \mathrm{v})$$

Note that we do not use color corrections here



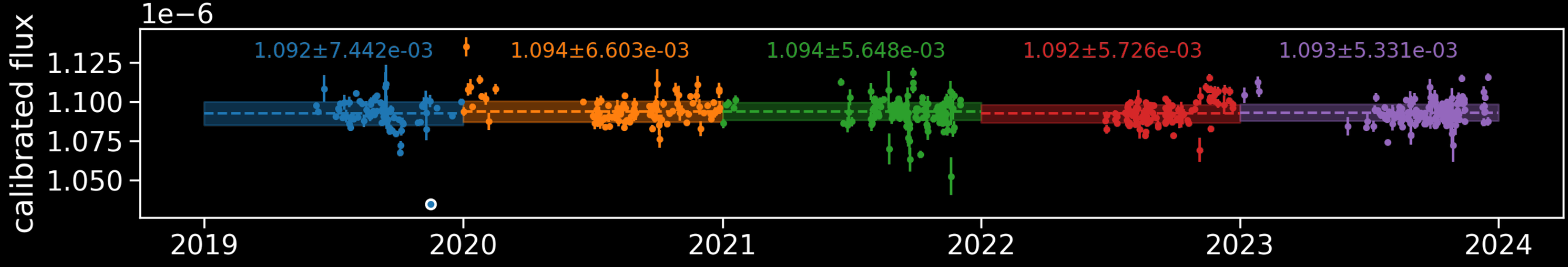
After calibration: relative precision of a few ‰



After calibration: relative precision of a few ‰

Here this is the light curve in the ztf g band of a star of magnitude gaia bp ~14.8

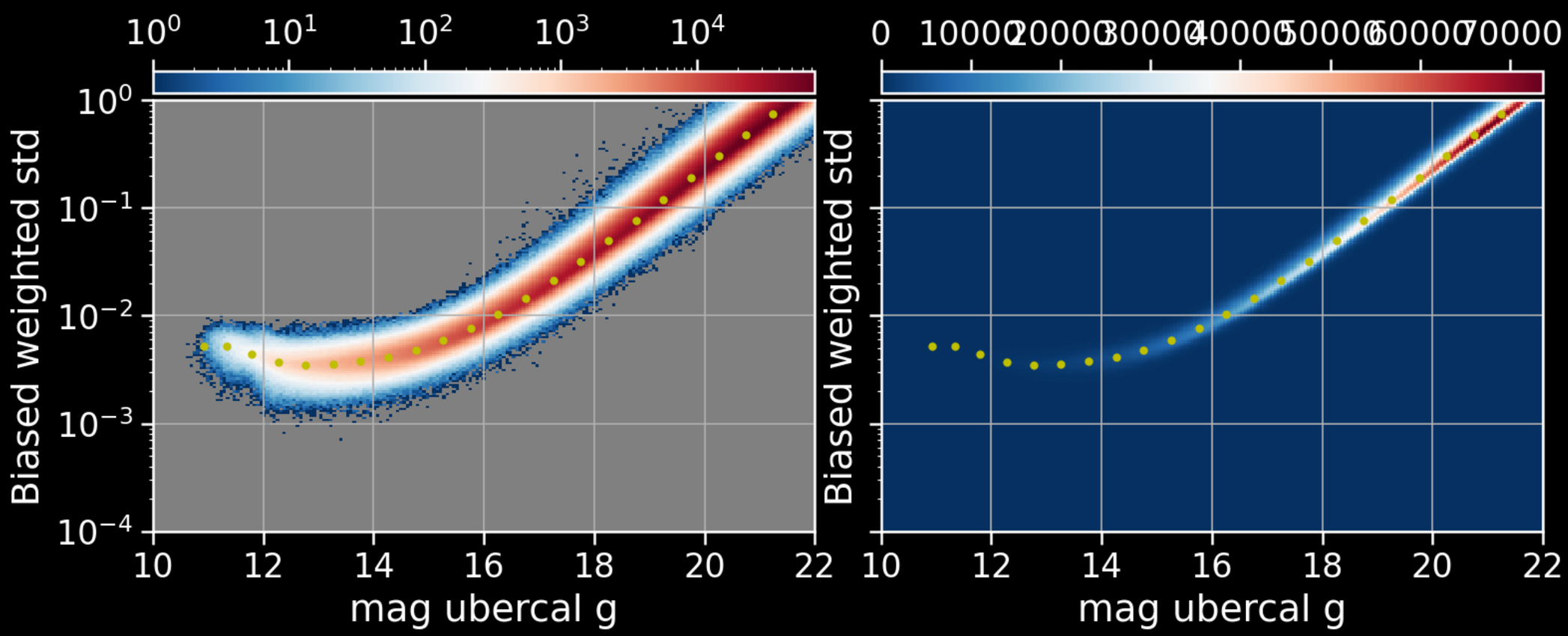
We can then combine these 5 yearly catalogs and get the **weighted standard deviation**

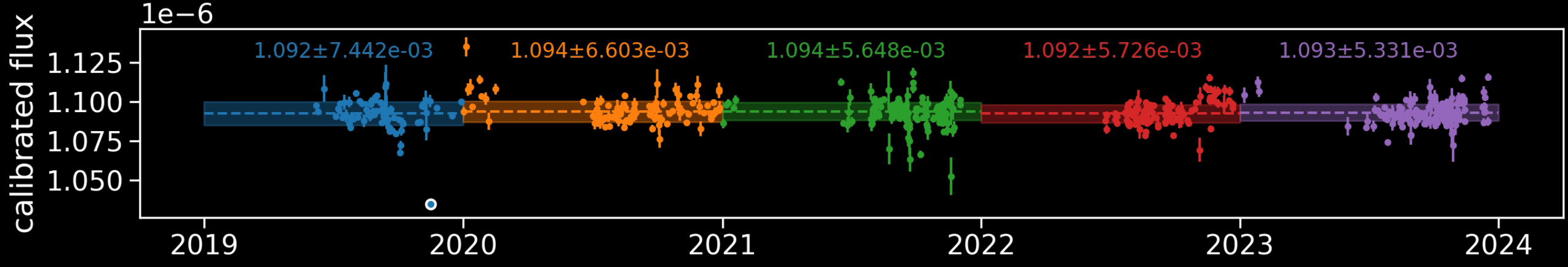


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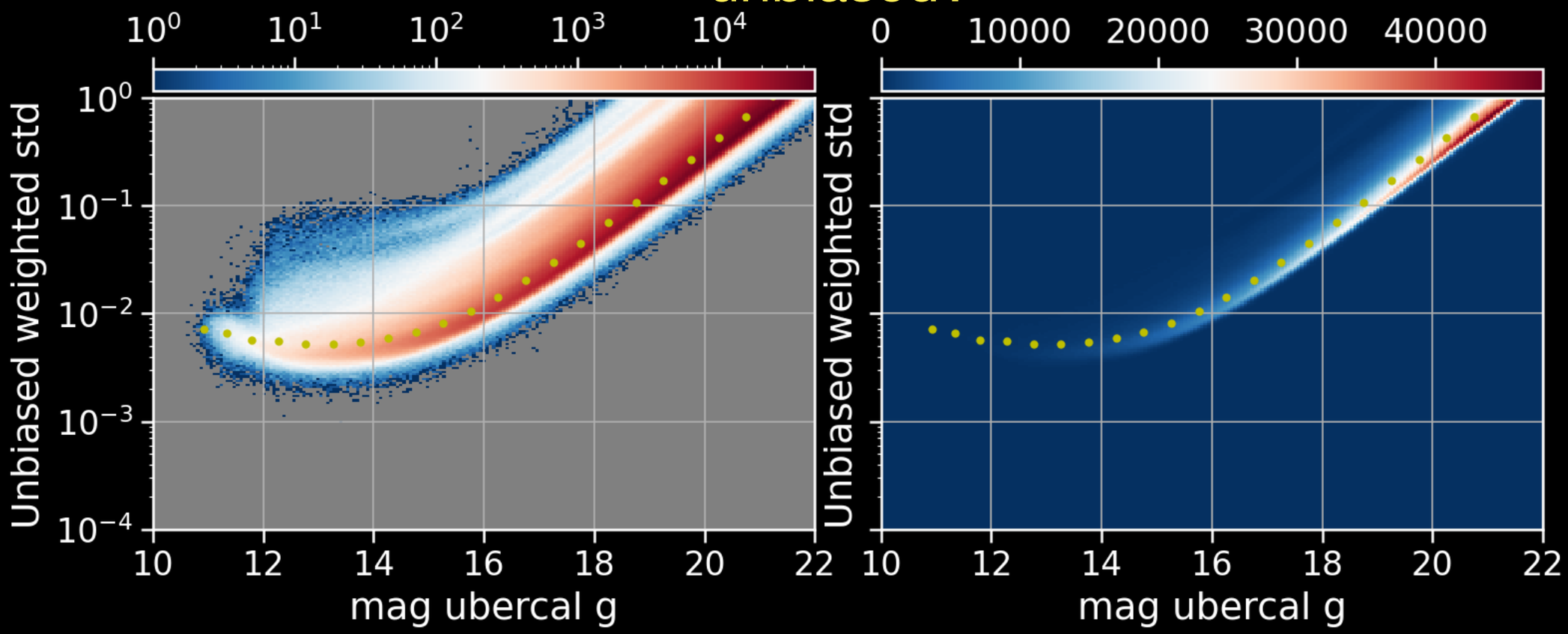


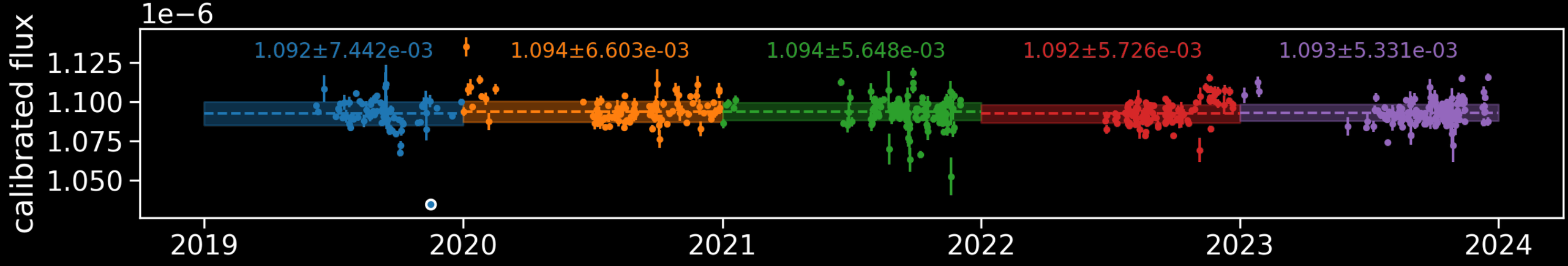
After calibration: relative precision of a few ‰

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We can then combine these 5 yearly catalogs and get the **weighted standard deviation**

unbiased?

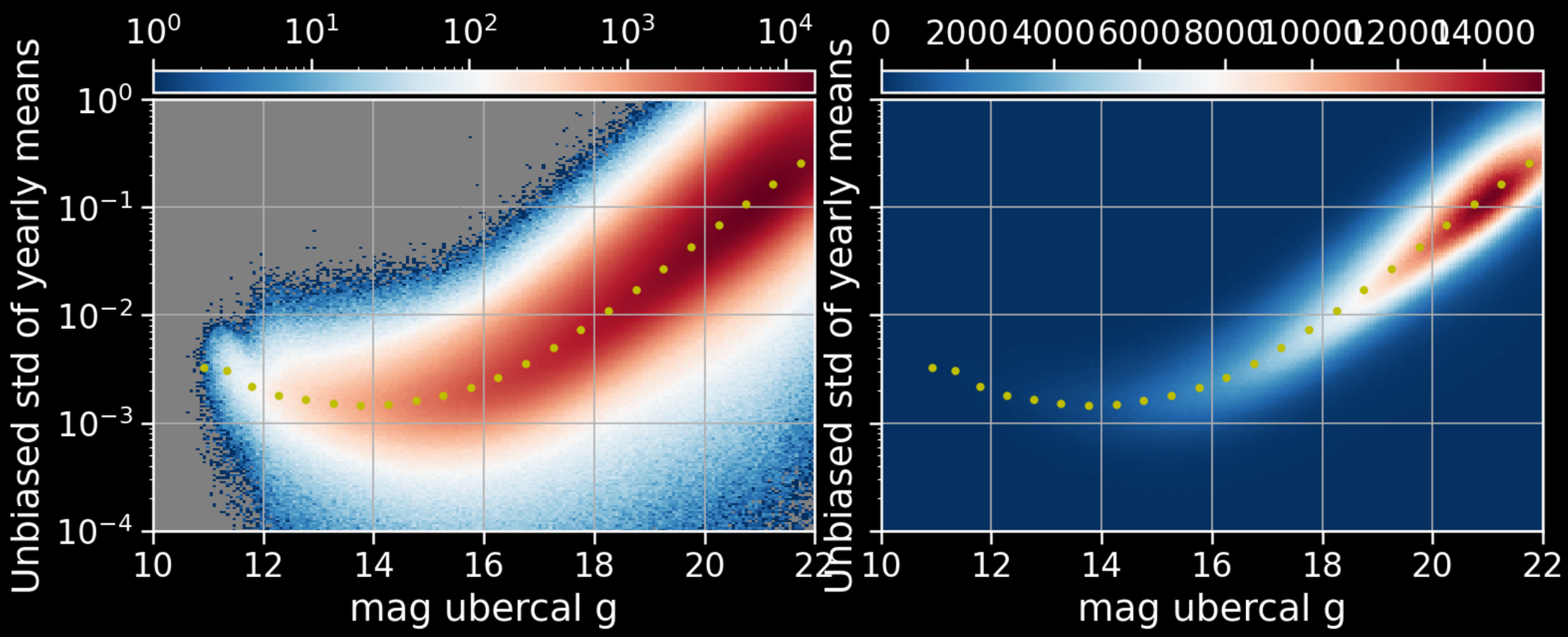


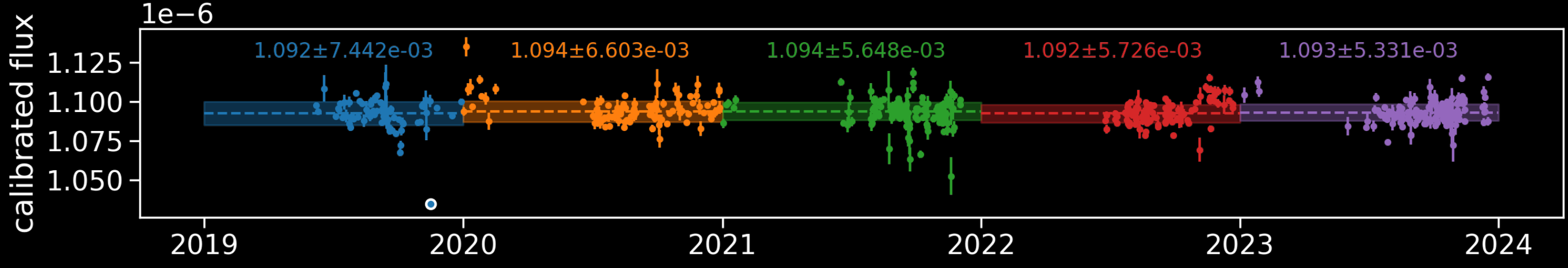


After calibration: relative precision of a few ‰

Here this is the light curve in the ztf g band of a star of magnitude gaia bp ~14.8

We can also check the **std of the yearly means**

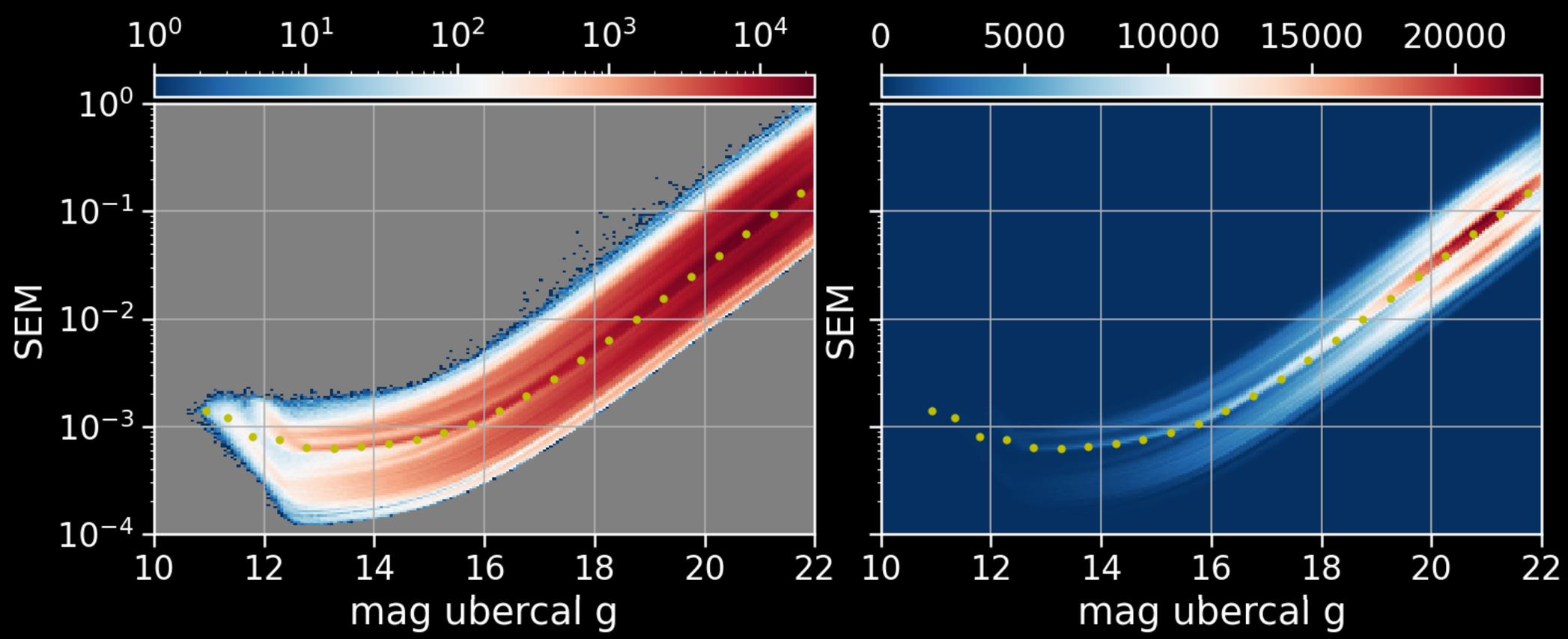




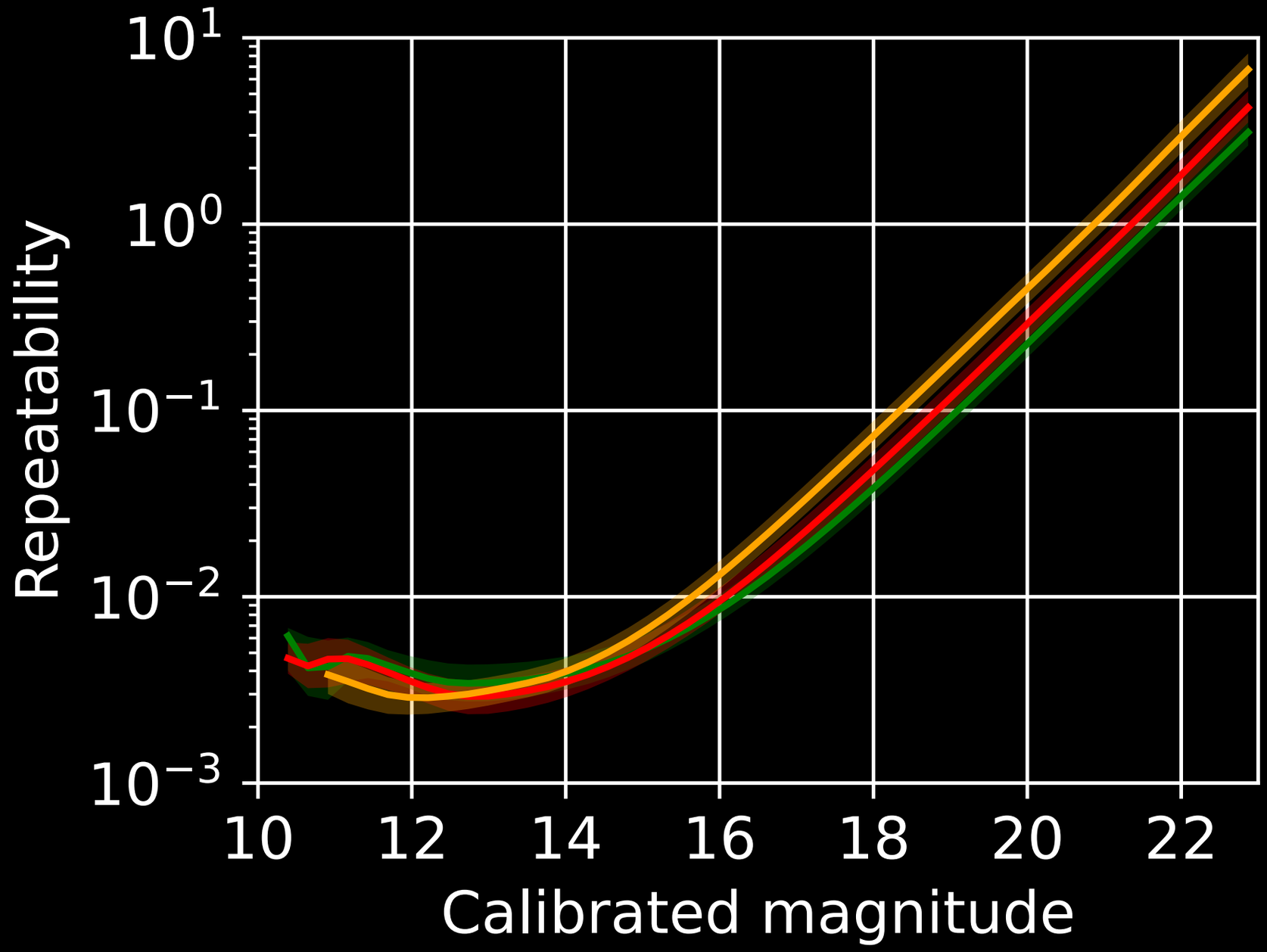
After calibration: relative precision of a few ‰

Here this is the light curve in the ztf g band of a star of magnitude gaia bp ~14.8

As well as the standard error on the mean (weighted and unbiased) of the whole thing

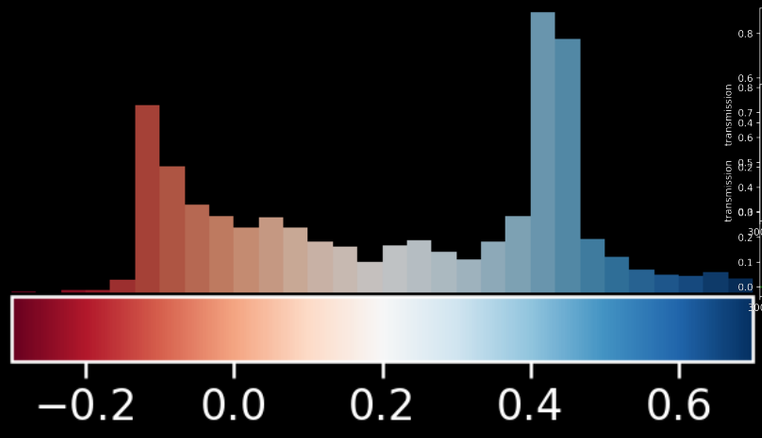


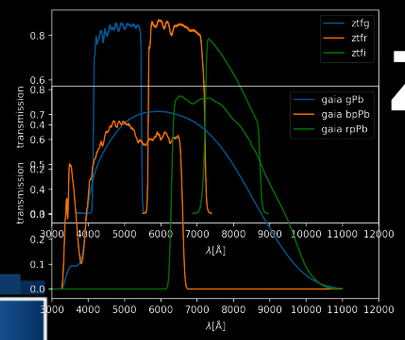
Here the **weighted standard deviation for the 3 bands**

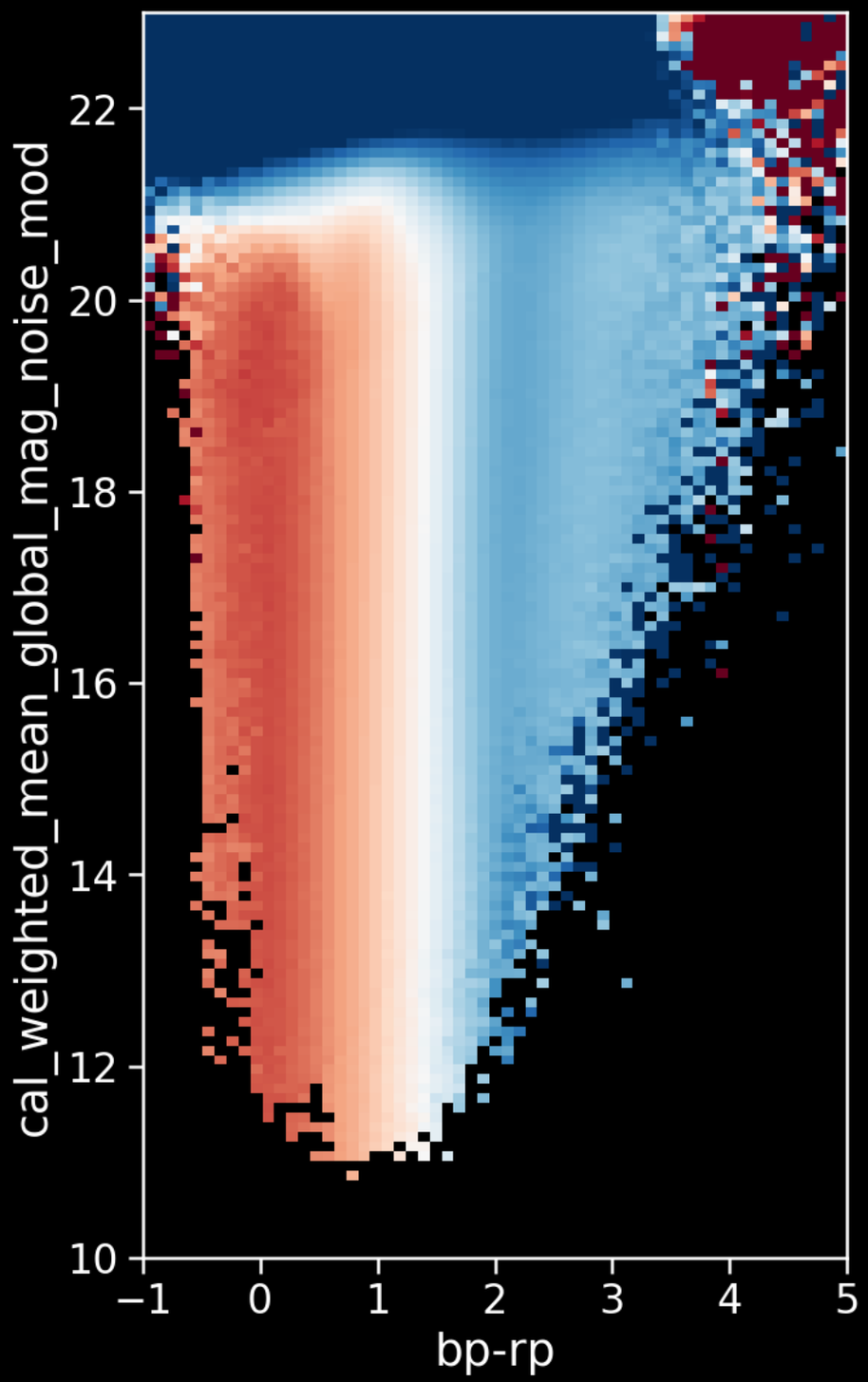


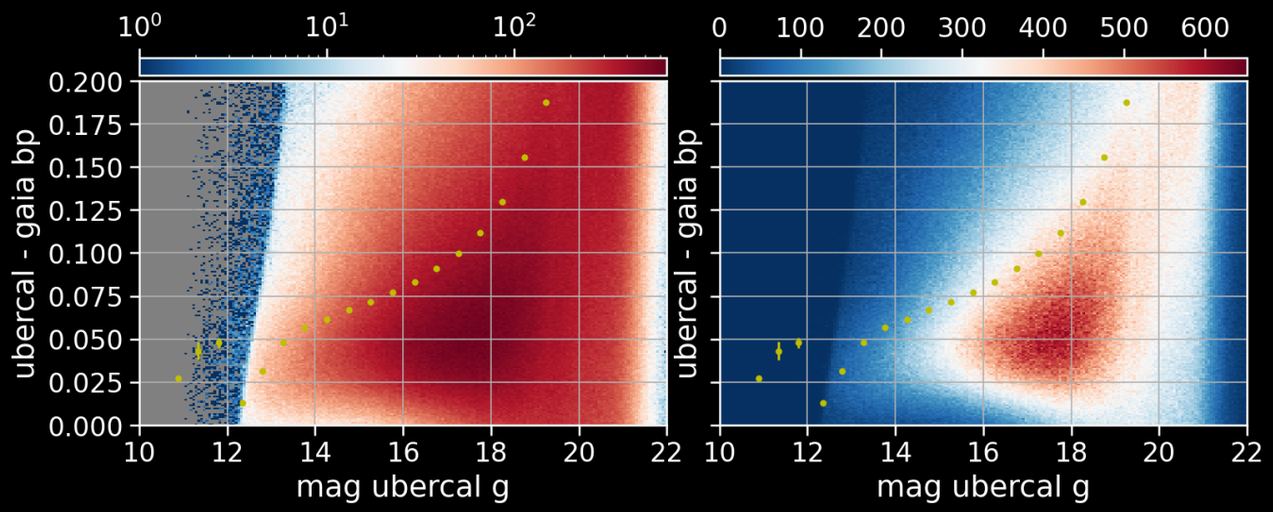
ZTF - Gaia Photometric

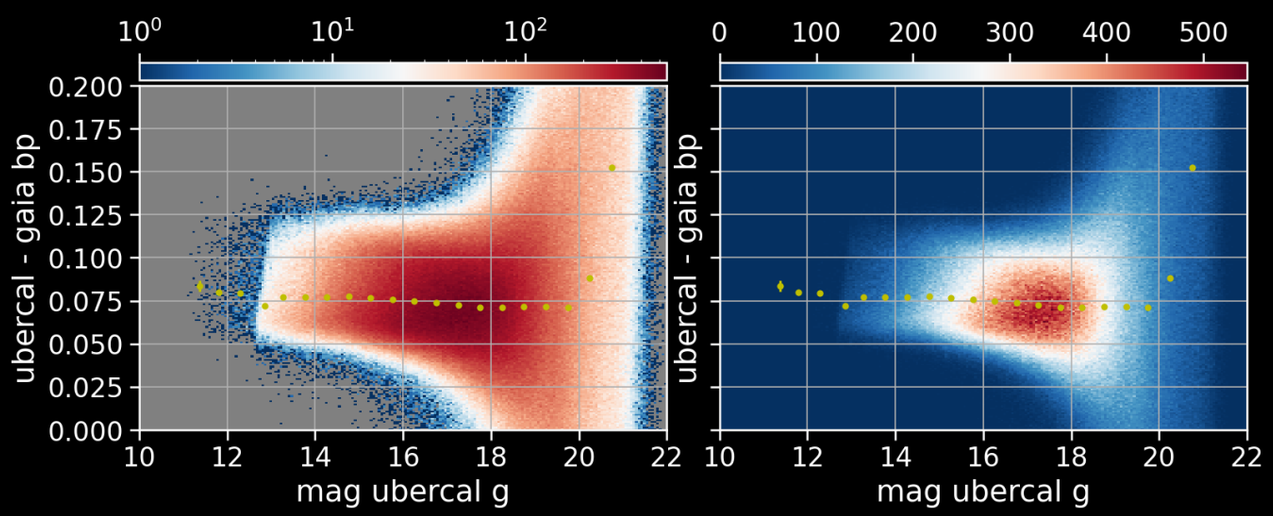
Here ZTF-g - gaia bp







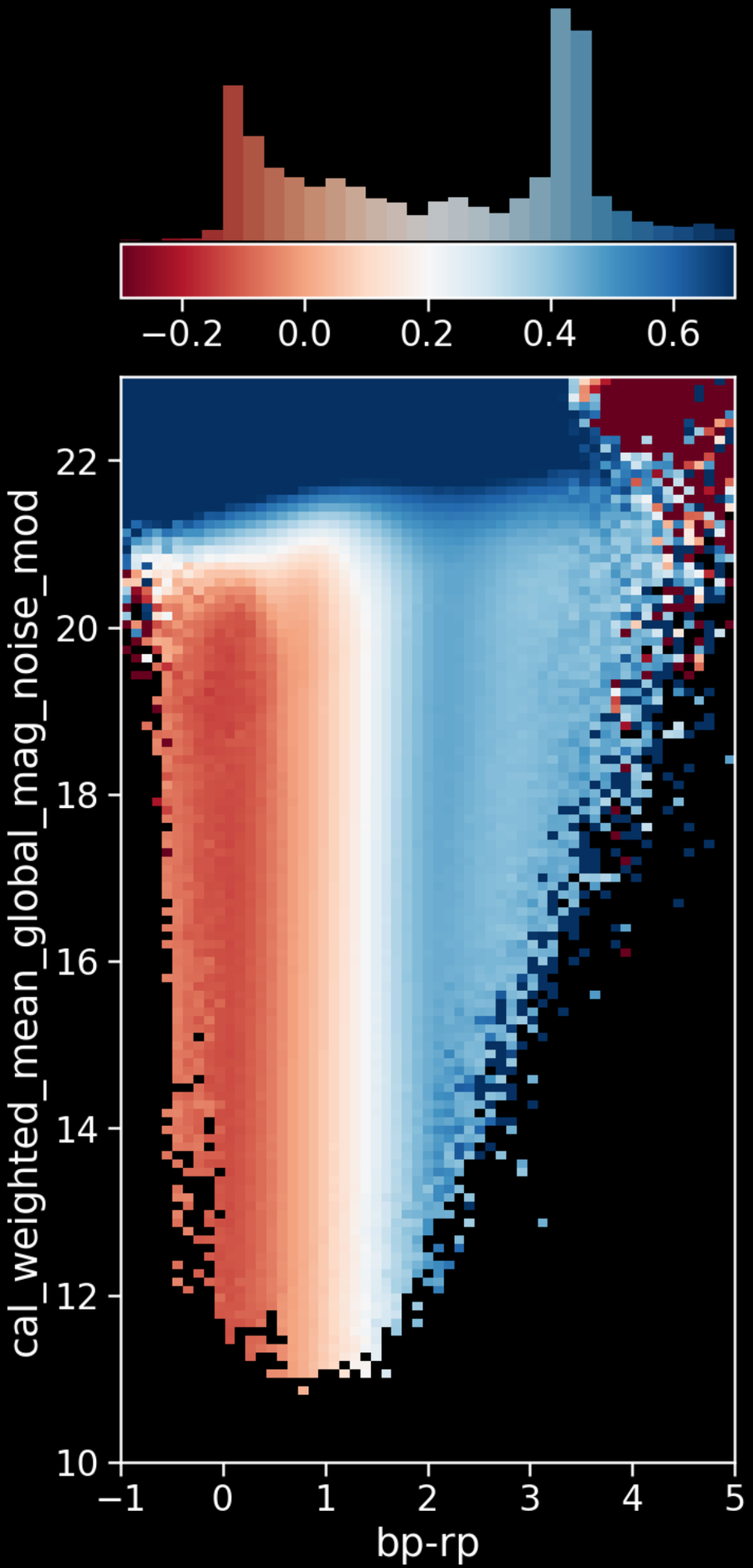


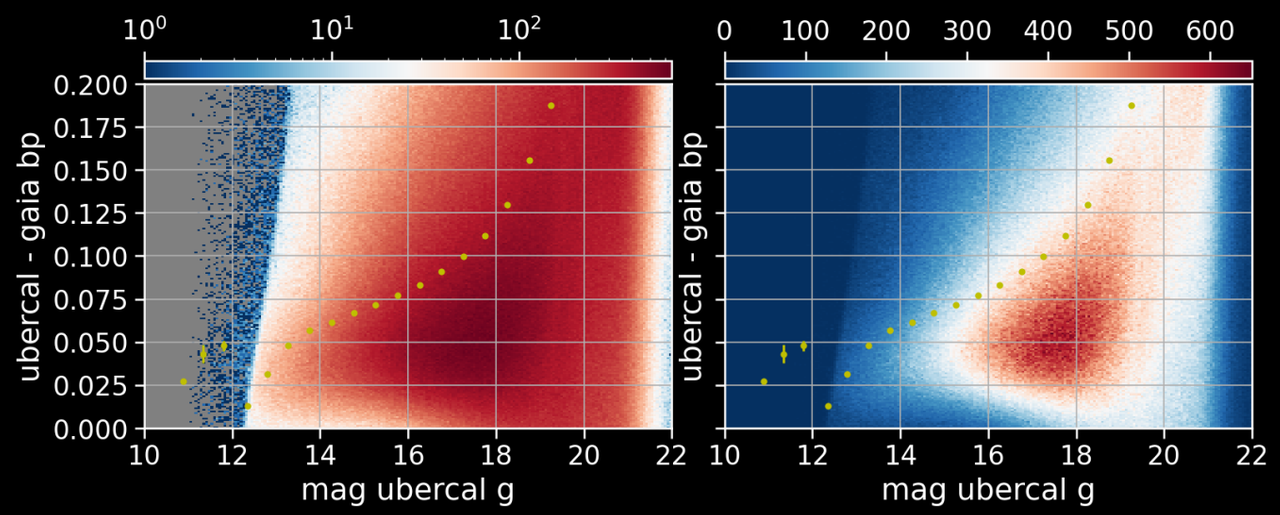


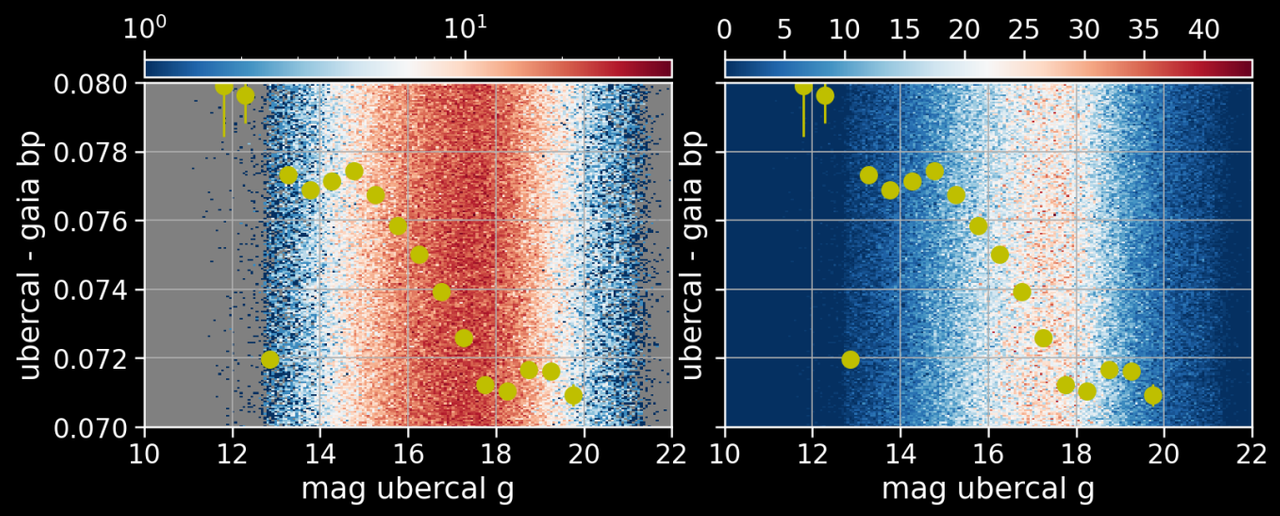
0.9<bp-rp<1.1

ZTF - Gaia Photometric

Here ZTF-g - gaia bp



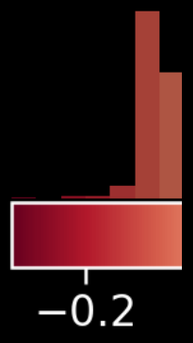


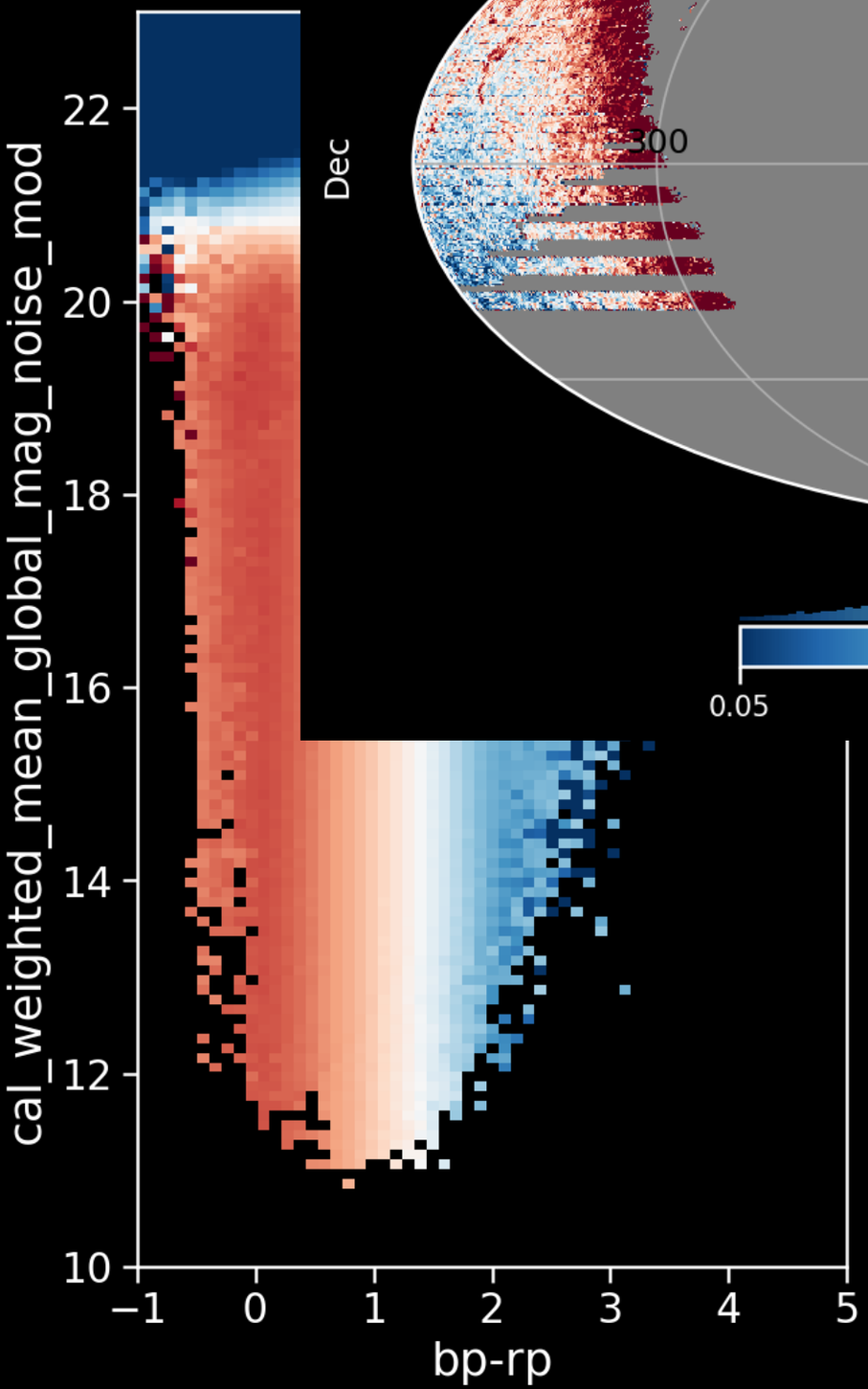


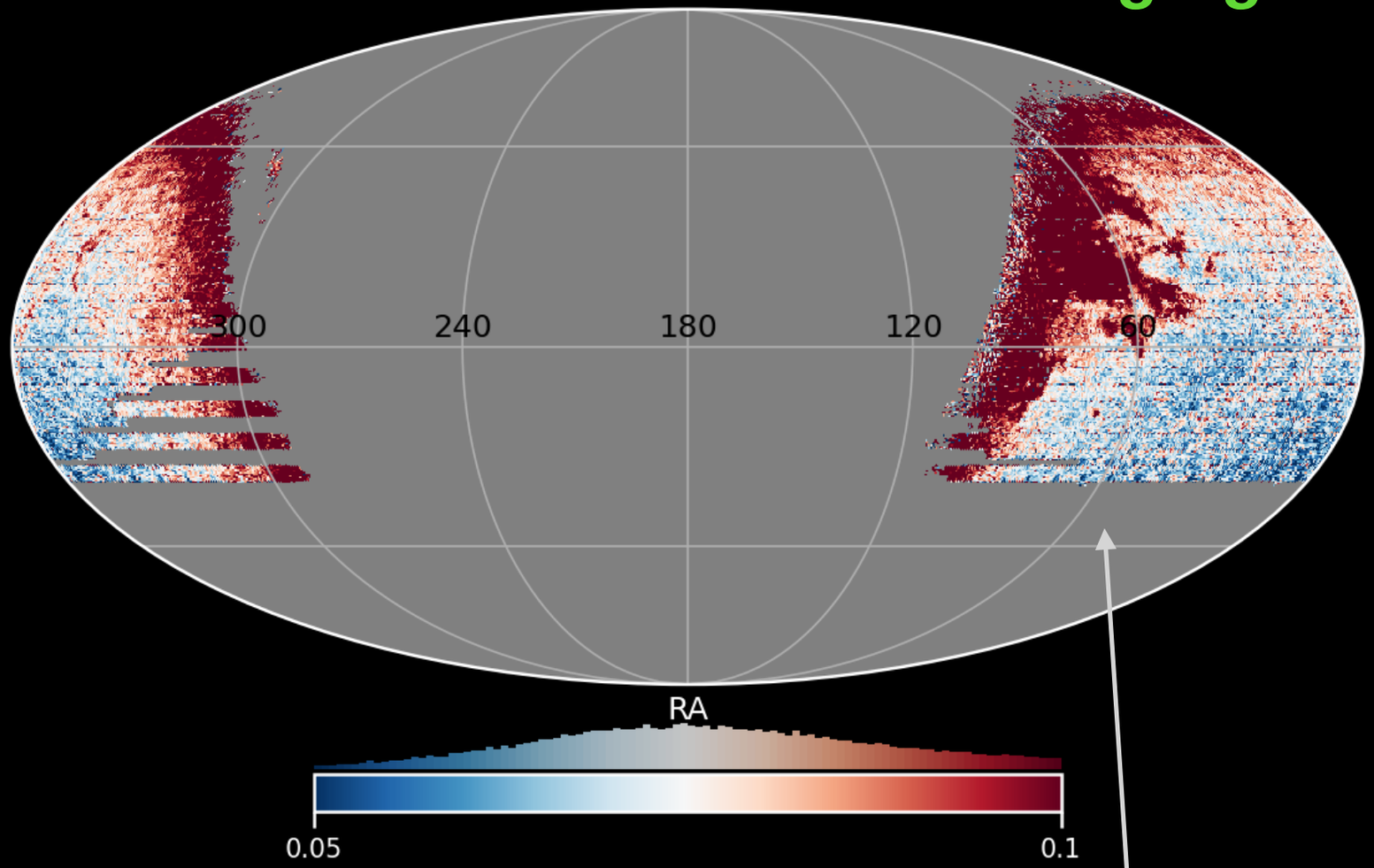
0.9<bp-rp<1.1

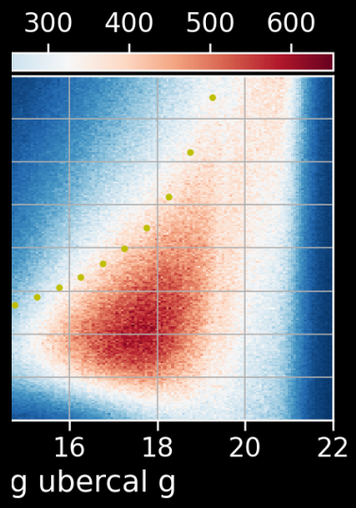
ZTF - Gaia Photometric

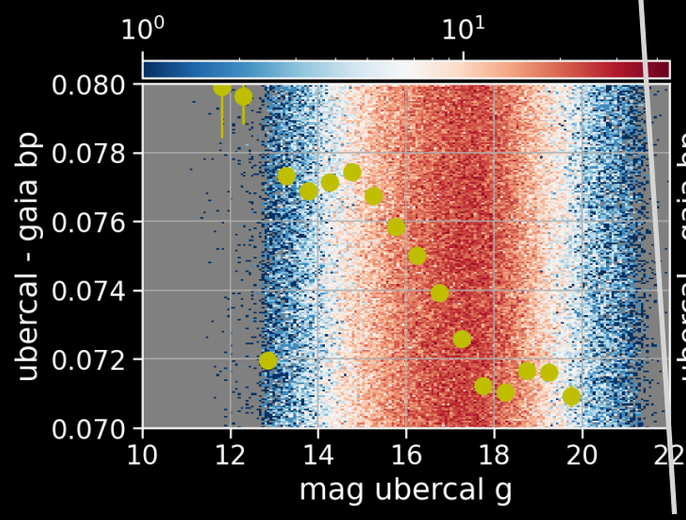
Here ZTF-g - gaia bp

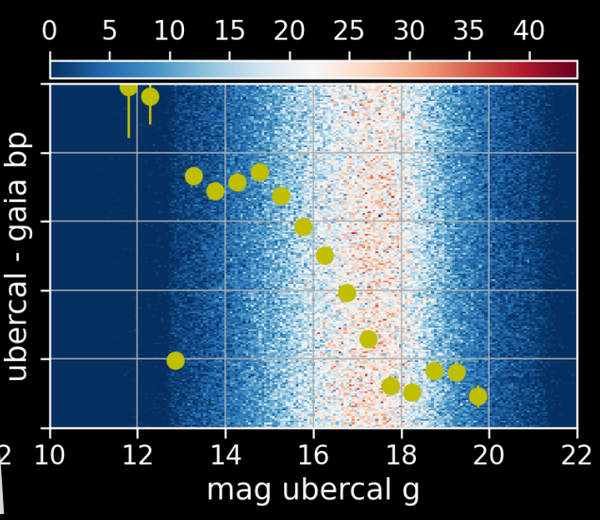










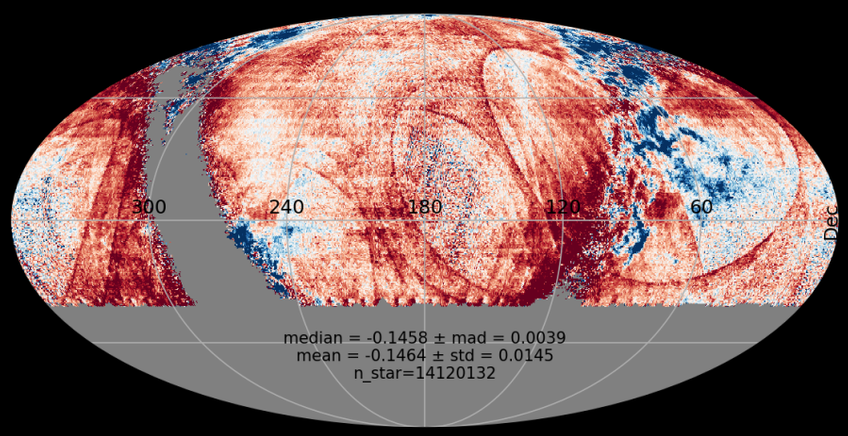


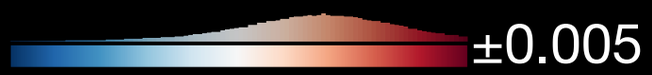
0.9<bp-rp<1.1

ZTF - Gaia Synthetic

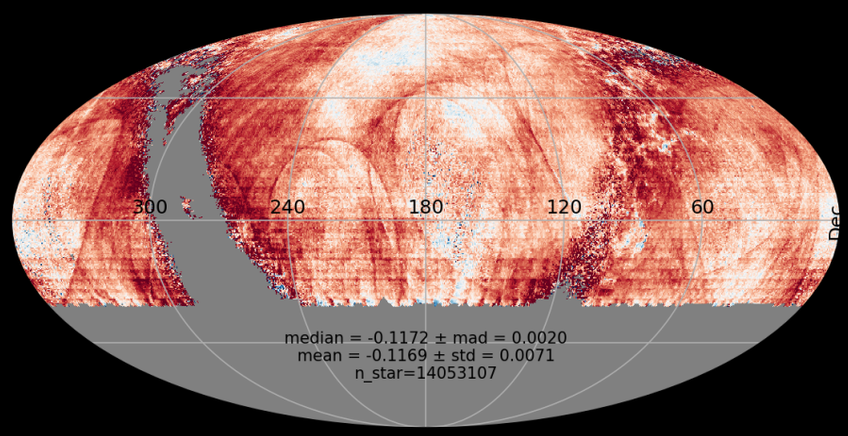
For each star in our repopulated catalog, we compute a **synthetic photometry from gaia spectra**, using:
- the airmass weighted mean (see Marc's notes, mean should be ok)
- the **filter model: ztf2::g** (and r and i)
  - for a given quadrant id and x and y weighted mean

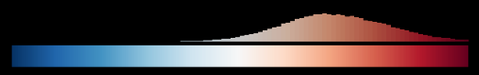
$$m_{\mathrm{syn},s}(X) = -2.5 \log_{10} \frac{\int S_s(\lambda)\, T(\lambda)\, A(\lambda)^X\, \lambda\, d\lambda}{\int S_{AB}(\lambda)\, T(\lambda)\, A(\lambda)^X\, \lambda\, d\lambda}$$



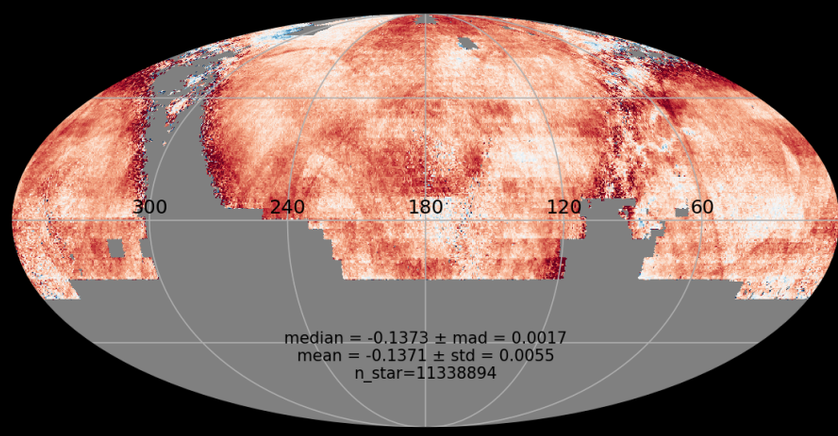


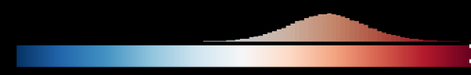
ZTF-g





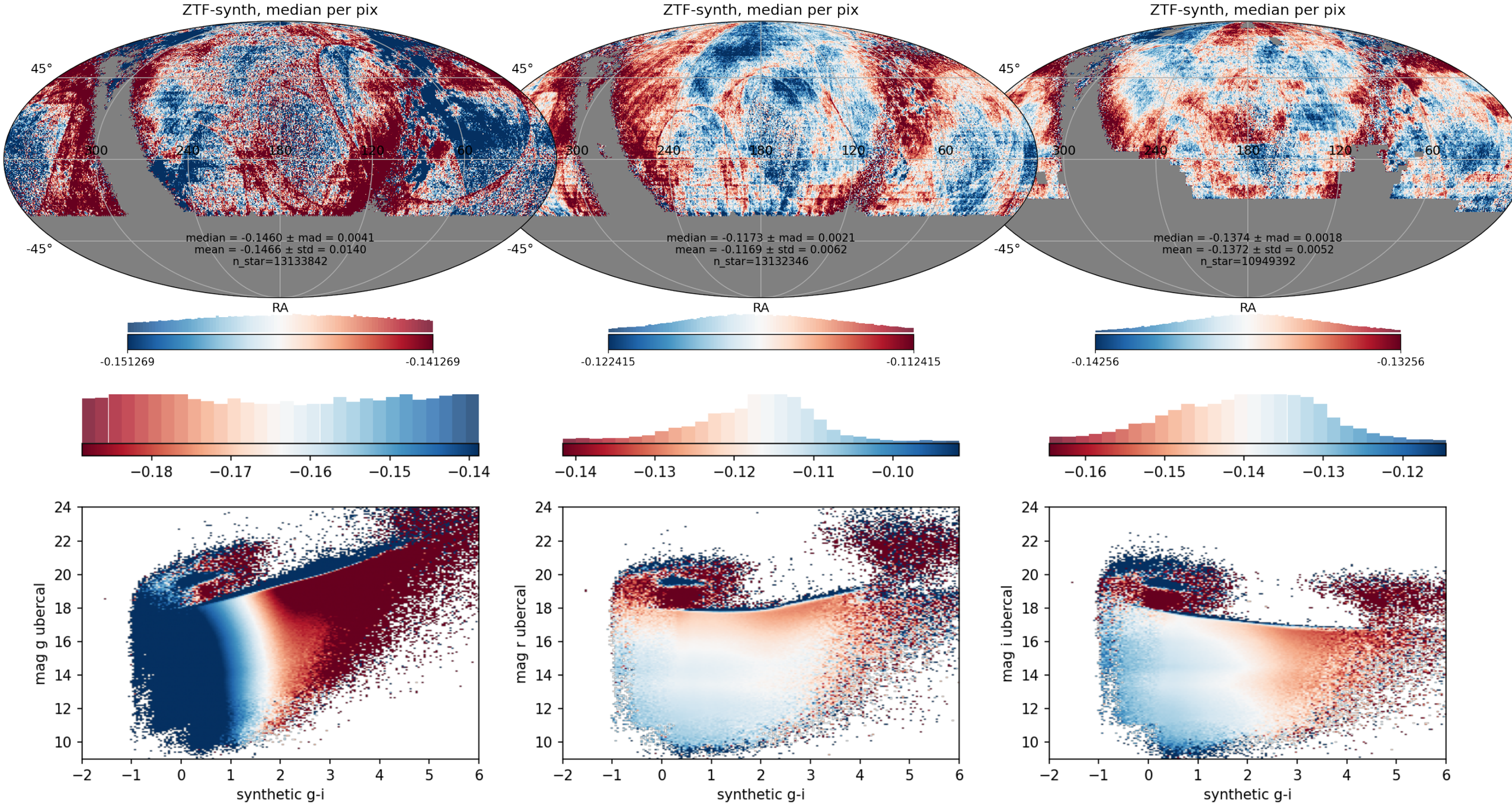
ZTF-r



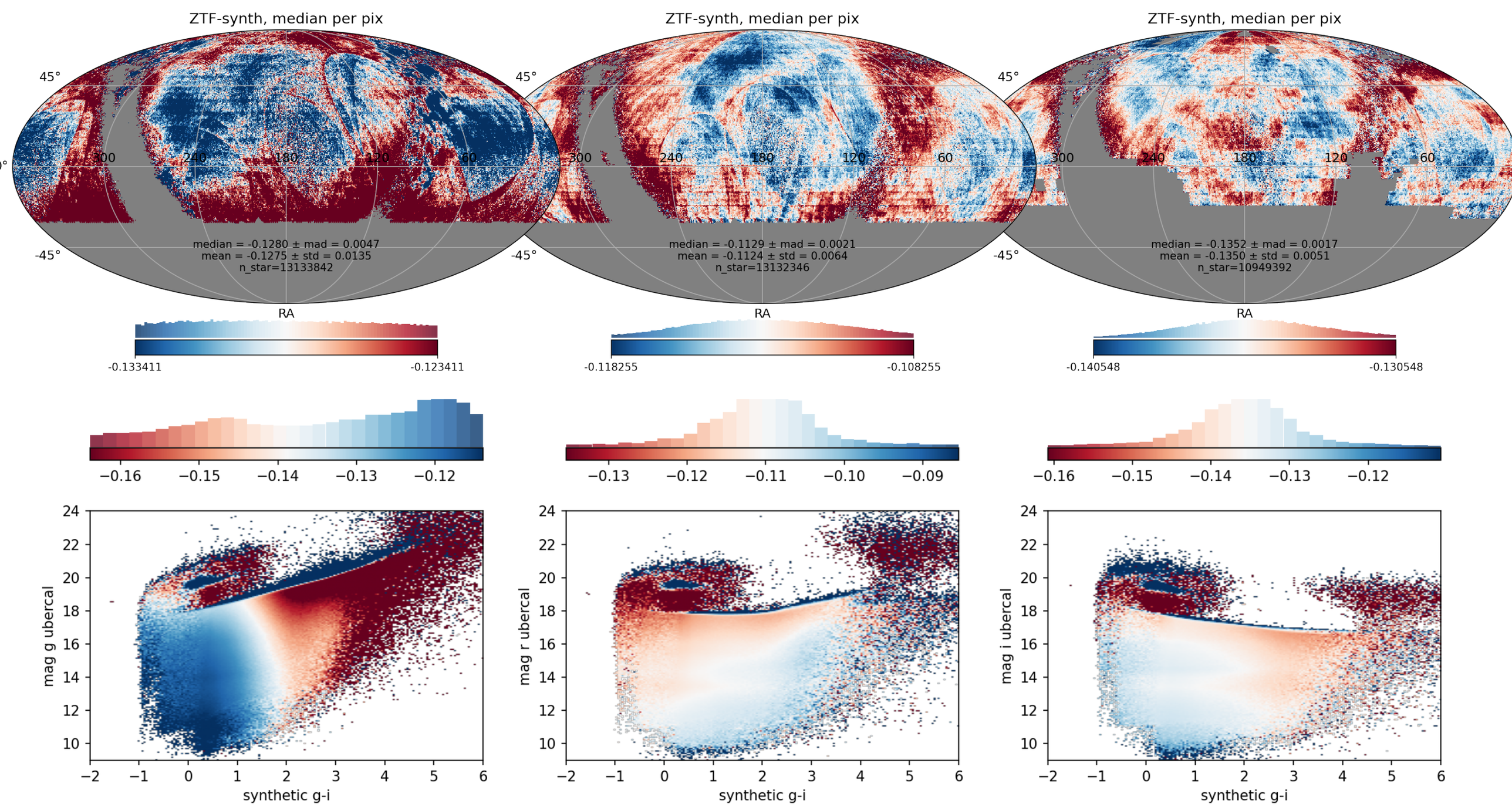


ZTF-i

Before correction



Original ubercal
no airmass in synthetic



Original ubercal
with airmass in synthetic

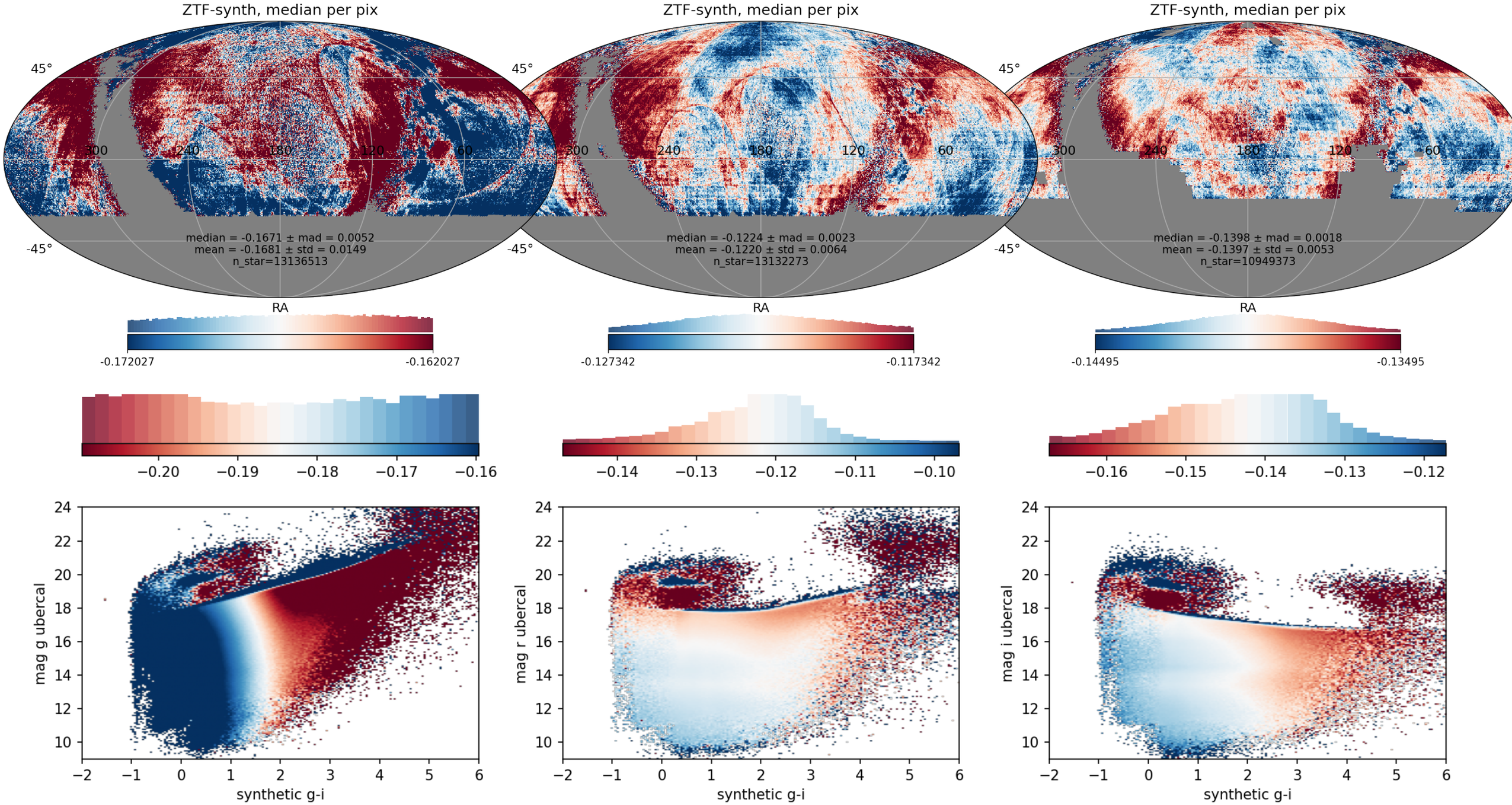
After correction

- Even though we fit k*X, this only corrects for a per exposure effect. The overall airmass term can still be left in the ZP. Since the atmosphere is not achromatic, it will depend on both the star population and the airmass.

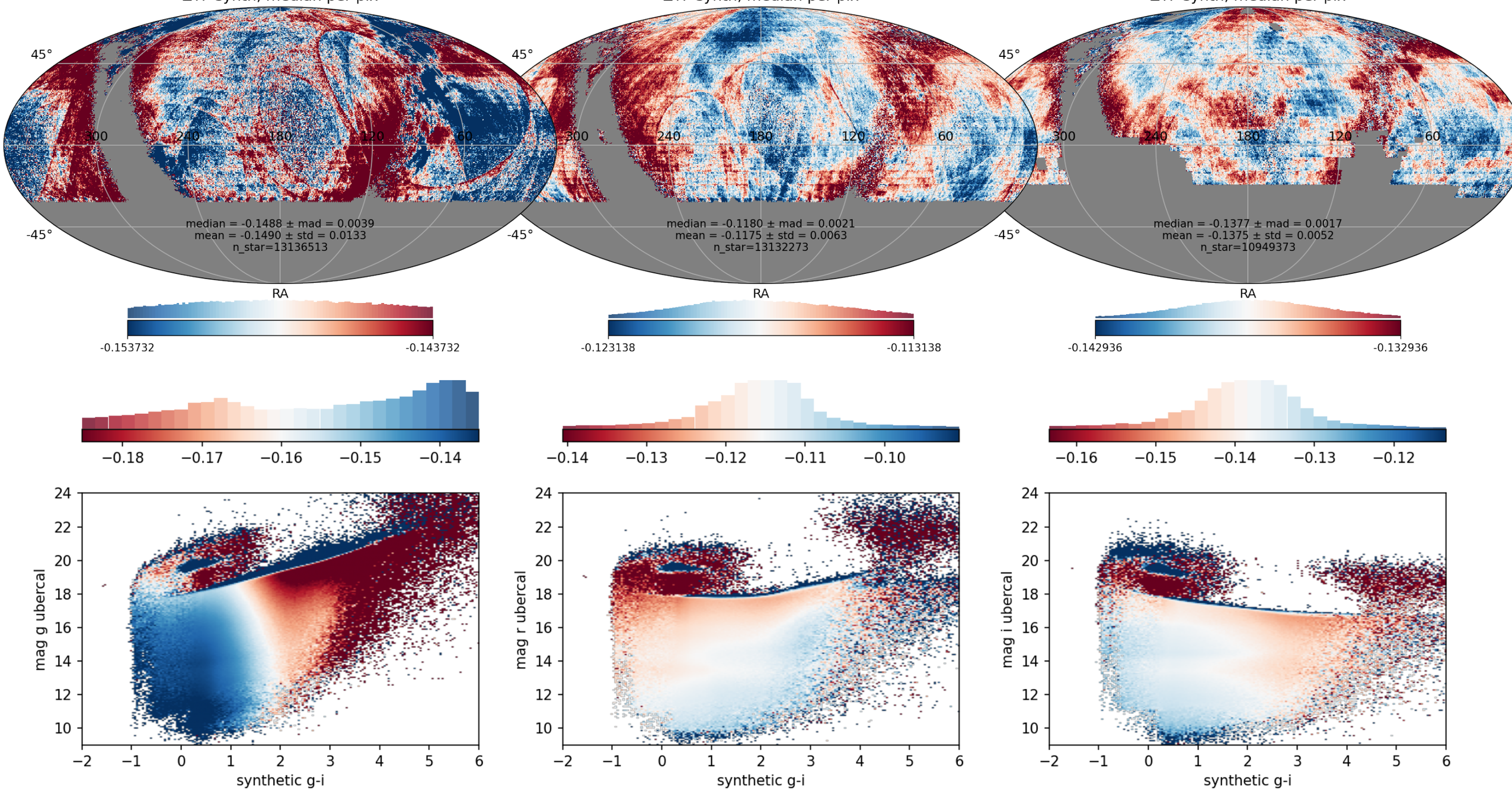
- Marc wrote some notes and concluded that the effect was equivalent to the difference between the synthetic photometry with (mean) airmass and the the one without. Here we average it for all observations that "contribute to" a Zp.

$$m - m_{syn}(|X_i|_i) = -2.5 \log_{10} \frac{\int S_{AB}(\lambda) T(\lambda) A(\lambda)^{|X_i|_i} \lambda d\lambda}{\int S_{ab}(\lambda) T(\lambda) \lambda d\lambda} + \left| -2.5 \log_{10} \frac{\int S_s(\lambda) T(\lambda) \lambda d\lambda}{\int S_s(\lambda) T(\lambda) A(\lambda)^{|X_i|_i} \lambda d\lambda} \right|_s \quad (2)$$

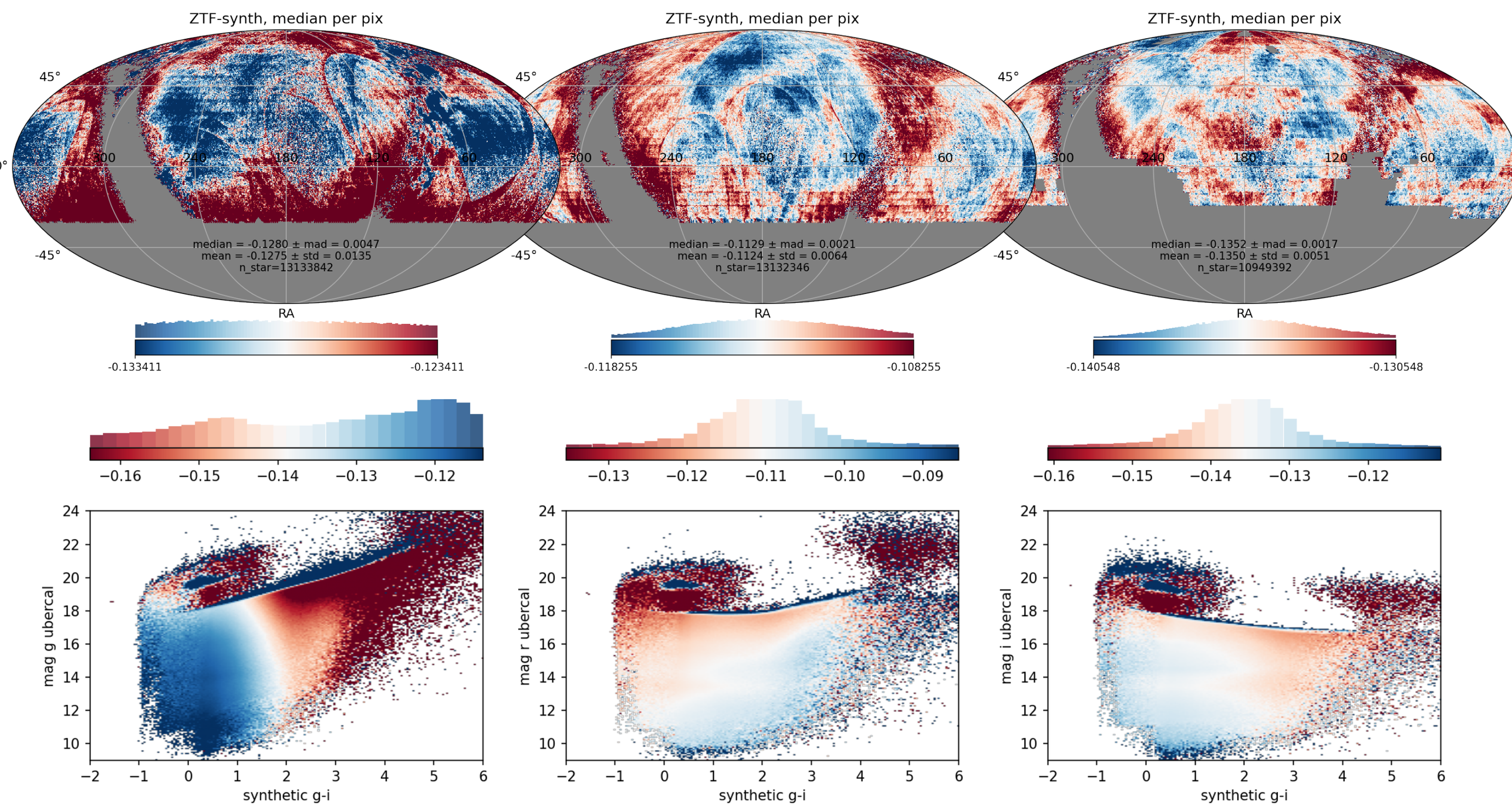
- We did this by preloading the last iteration of ubercal, taking the exposure ids (expid) and keeping only the observations that survived the cuts, and recovered the synthetic photometry for those. We then averaged per expid.
  - Caveat 1: The average here is a weighted average of the airmass over the 5 years that are in the repopulation, even though the correction could be per ubercal run. this assumes that the airmass distribution does not vary significantly between years. Reasonable but TBC.
  - Caveat 2: We can only do the average over the stars that have a gaia spectrum, so this is not really taking all stars that "enter the Zp".
  - Caveat 3: We use an old model of the filters (ztf2)
- We then have this lookup table for each exposure of a "synthetic correction", and we add it to the Zp when performing repopulation.



Corrected ubercal
no airmass in synthetic



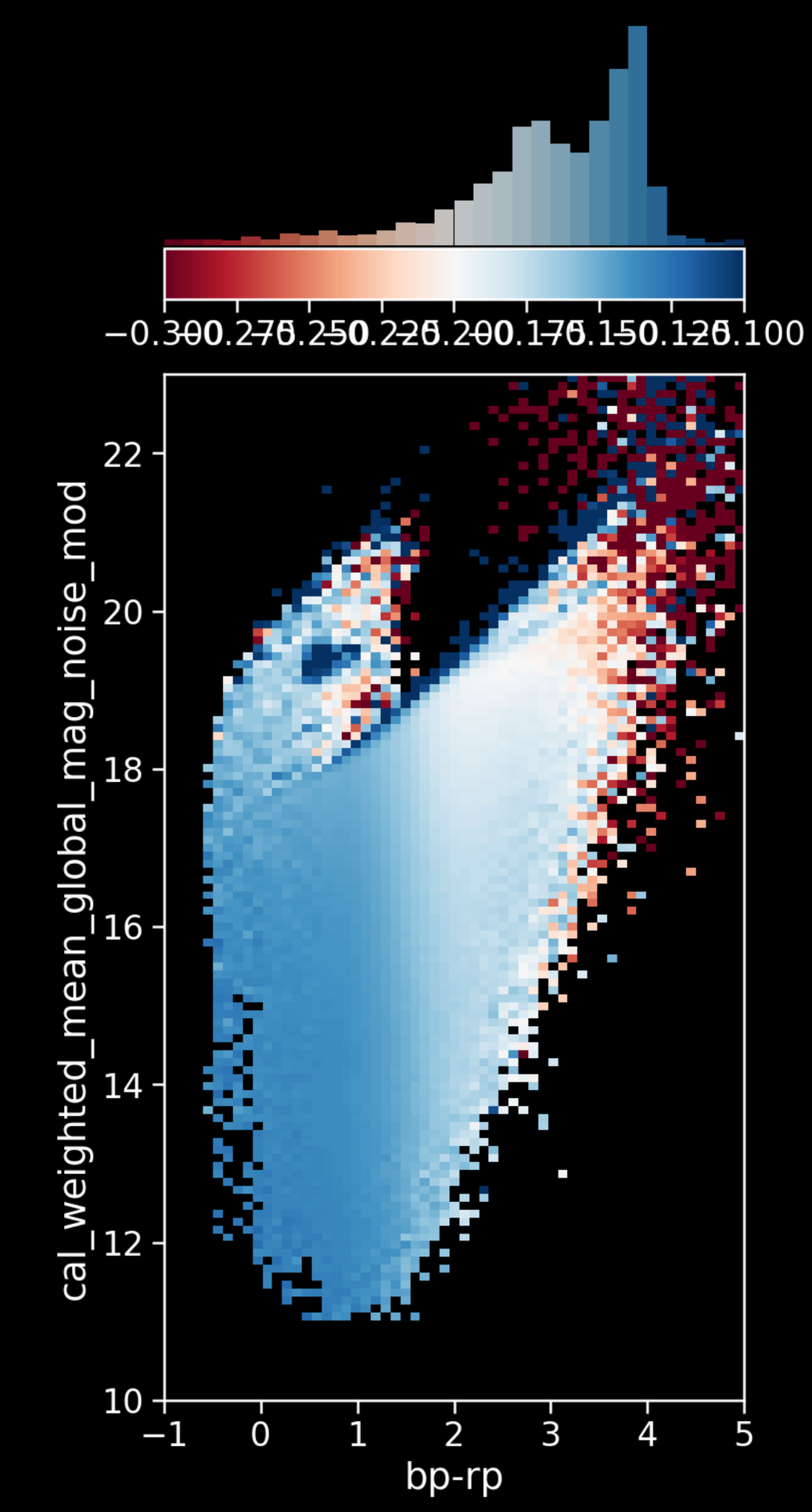
Corrected ubercal with airmass in synthetic

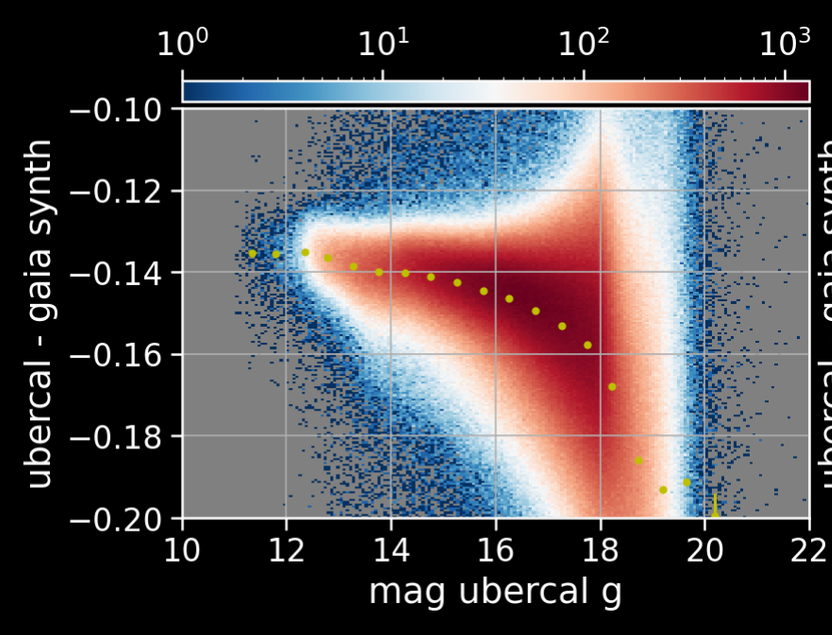


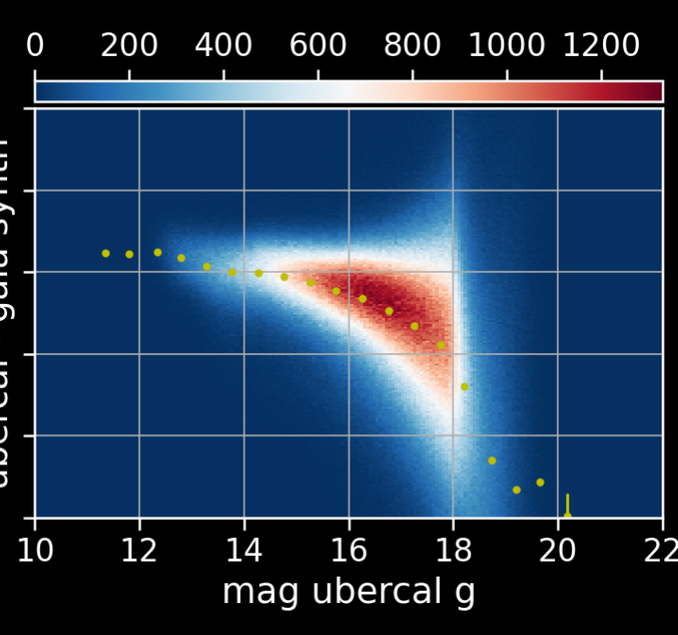
Original ubercal
with airmass in synthetic

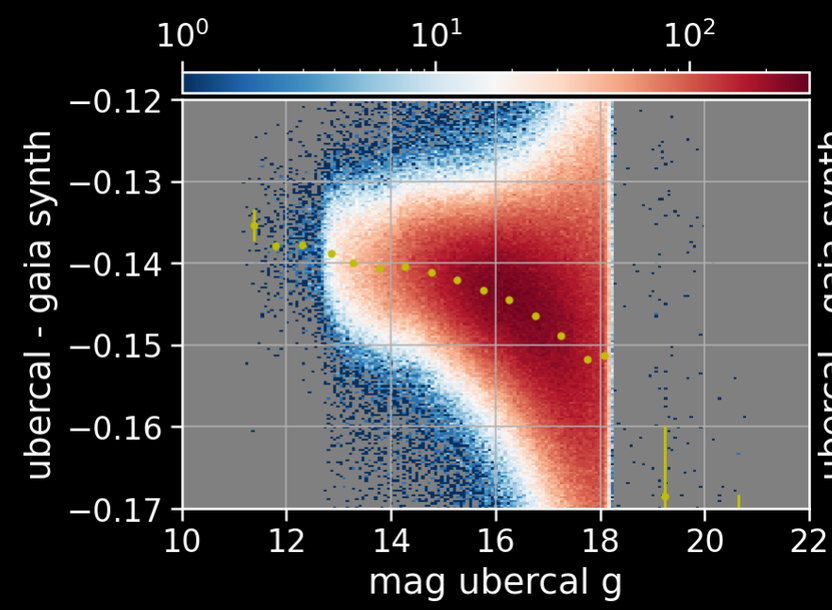
ZTF - Gaia Synthetic

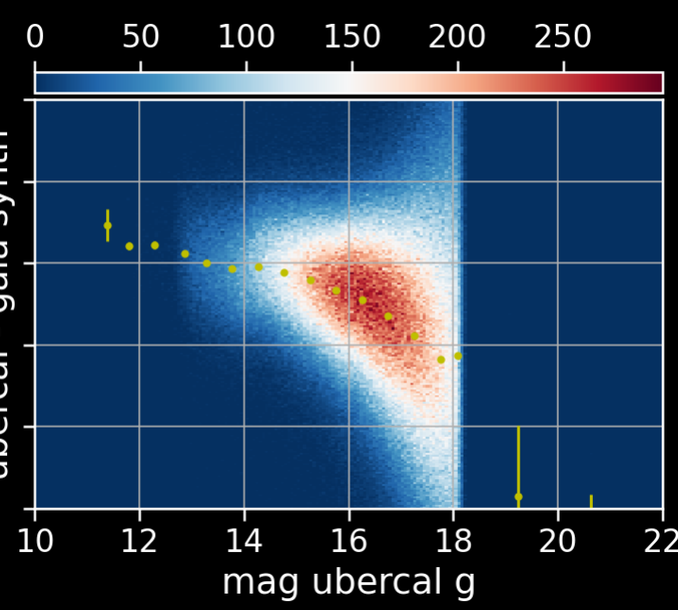
Here ZTF-g - gaia synthetic





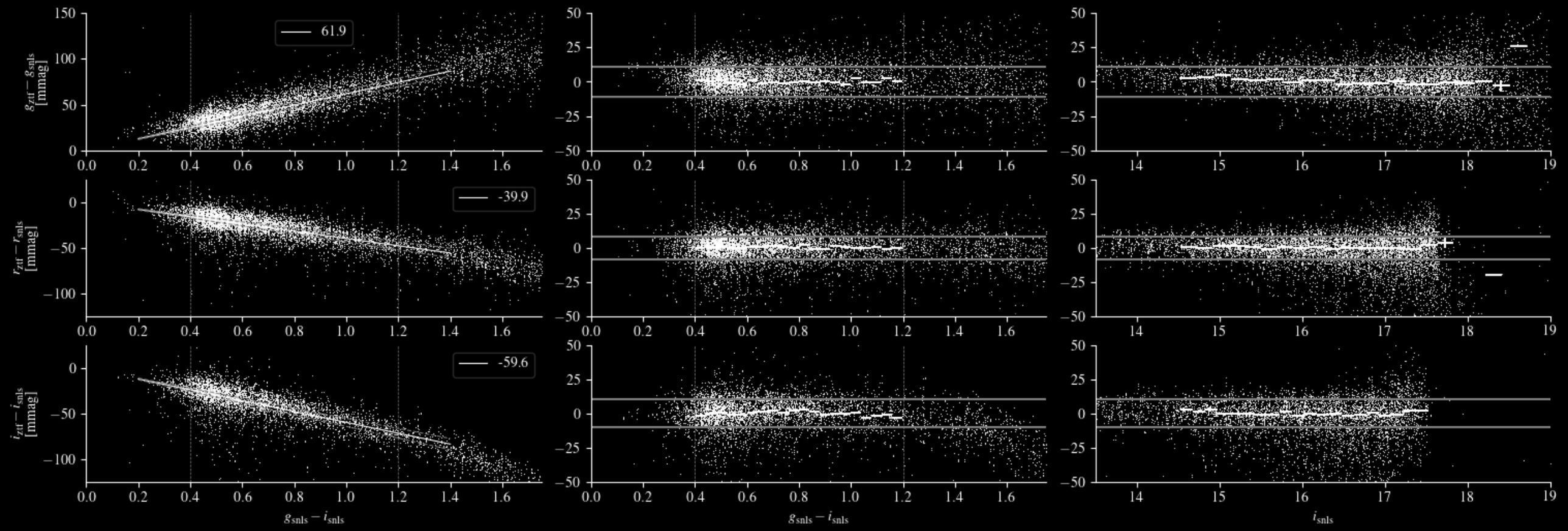


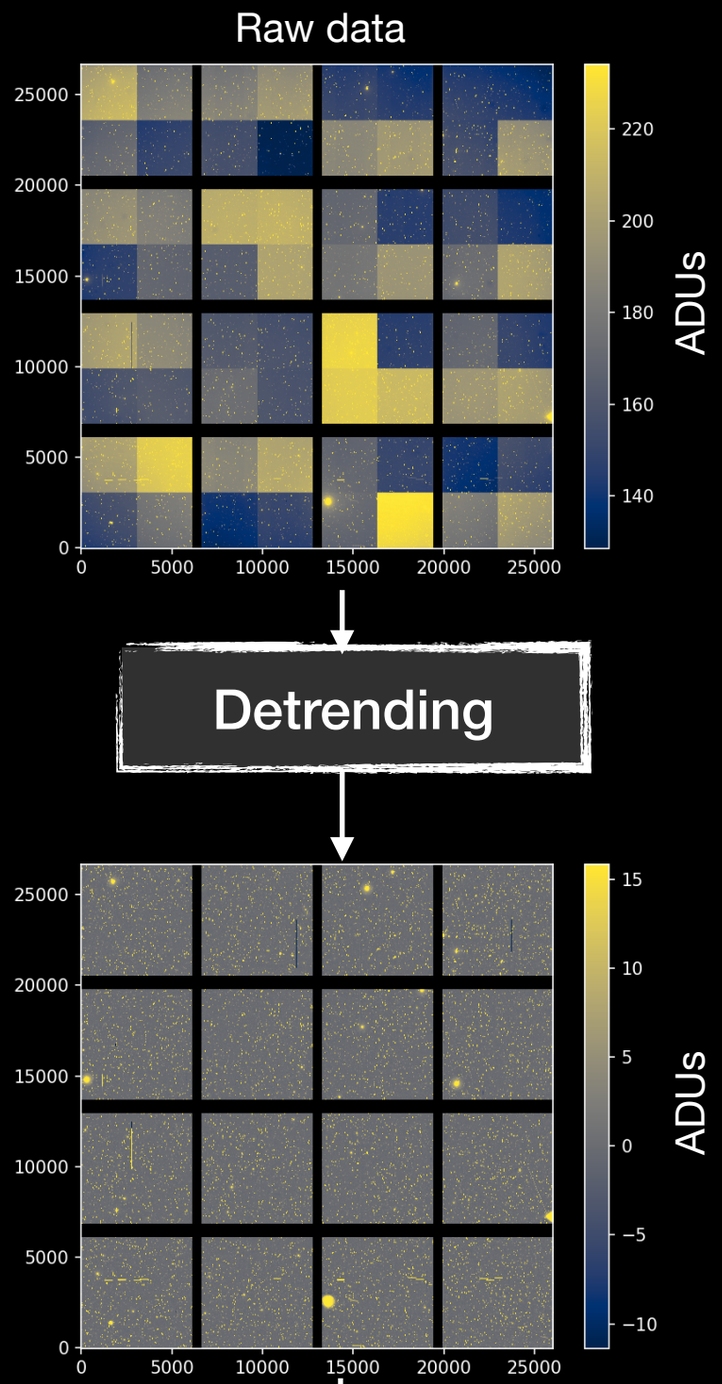




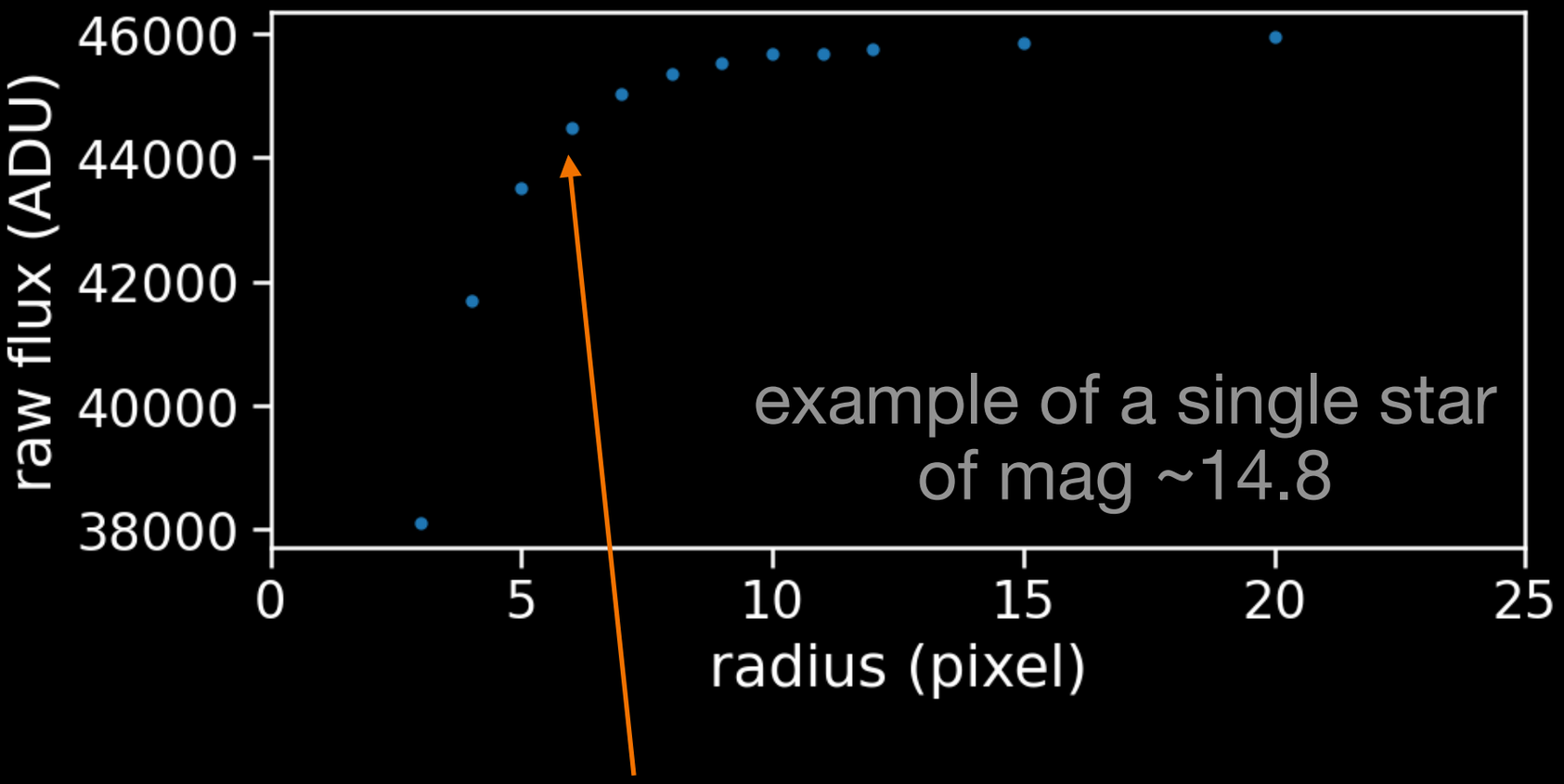
0.9<bp-rp<1.1

Golden plot?
SNLS vs ZTF seems ok.
See Maude's talk

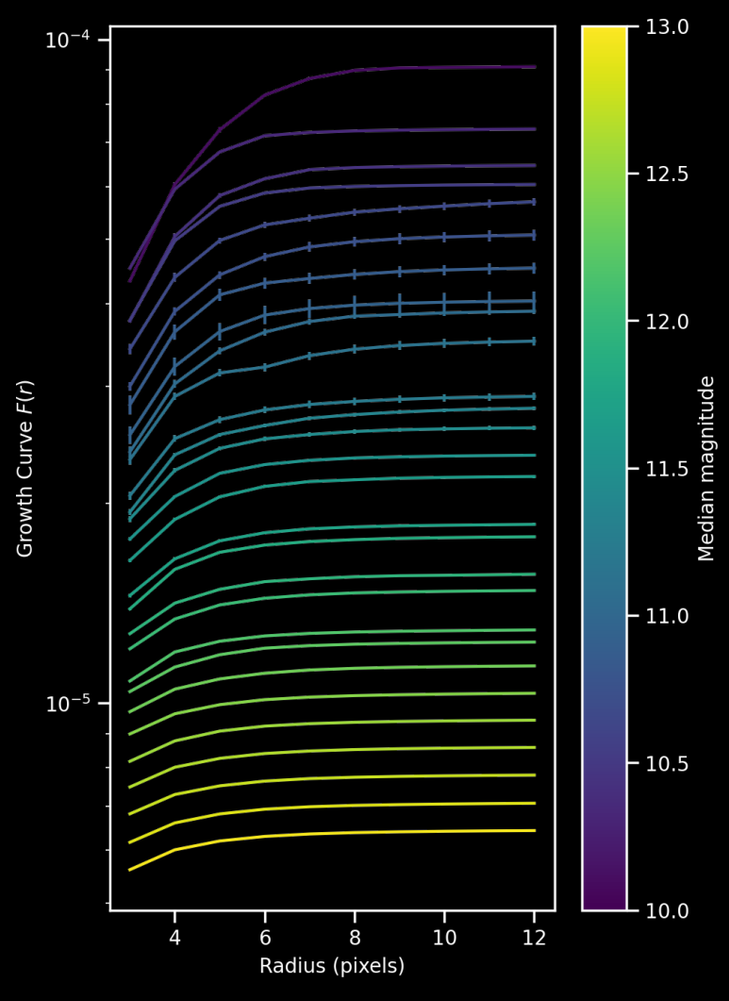


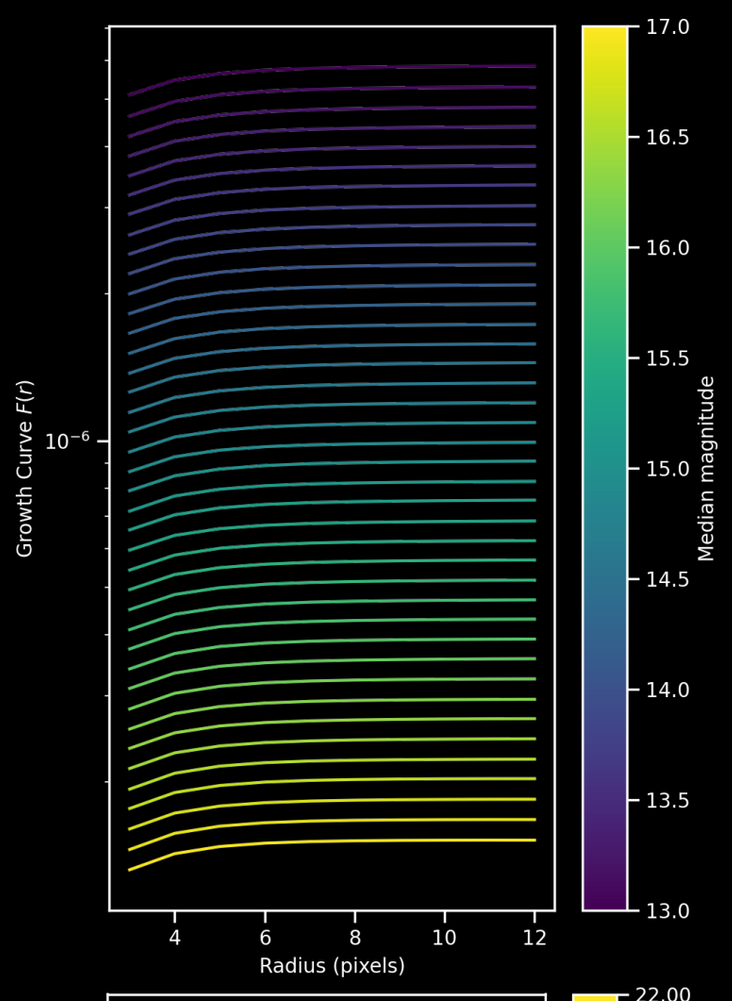


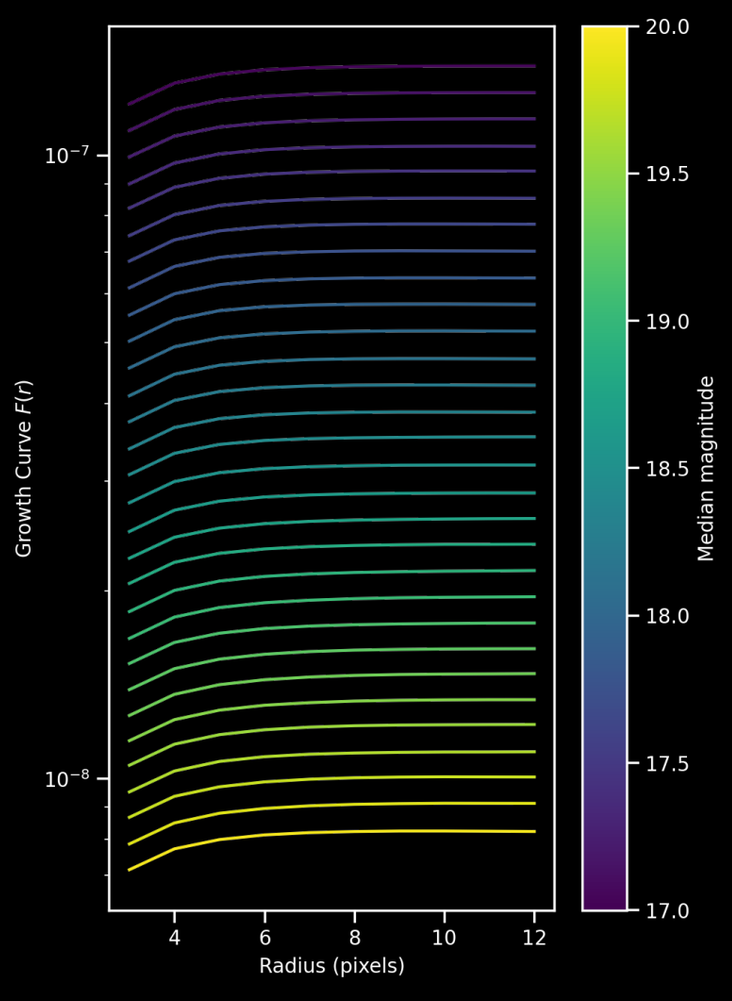
We get the aperture photometry flux
in ADU
for every gaia star
for multiple radii

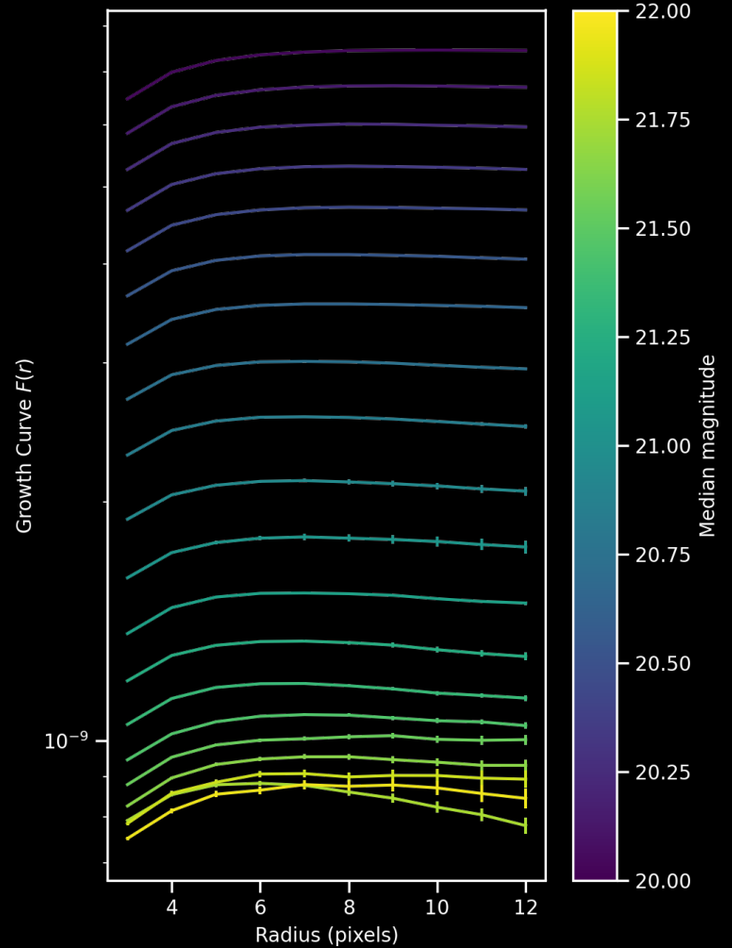


We use a radius of 6 pixels









REDO for 2019
(looks different at high mag…)

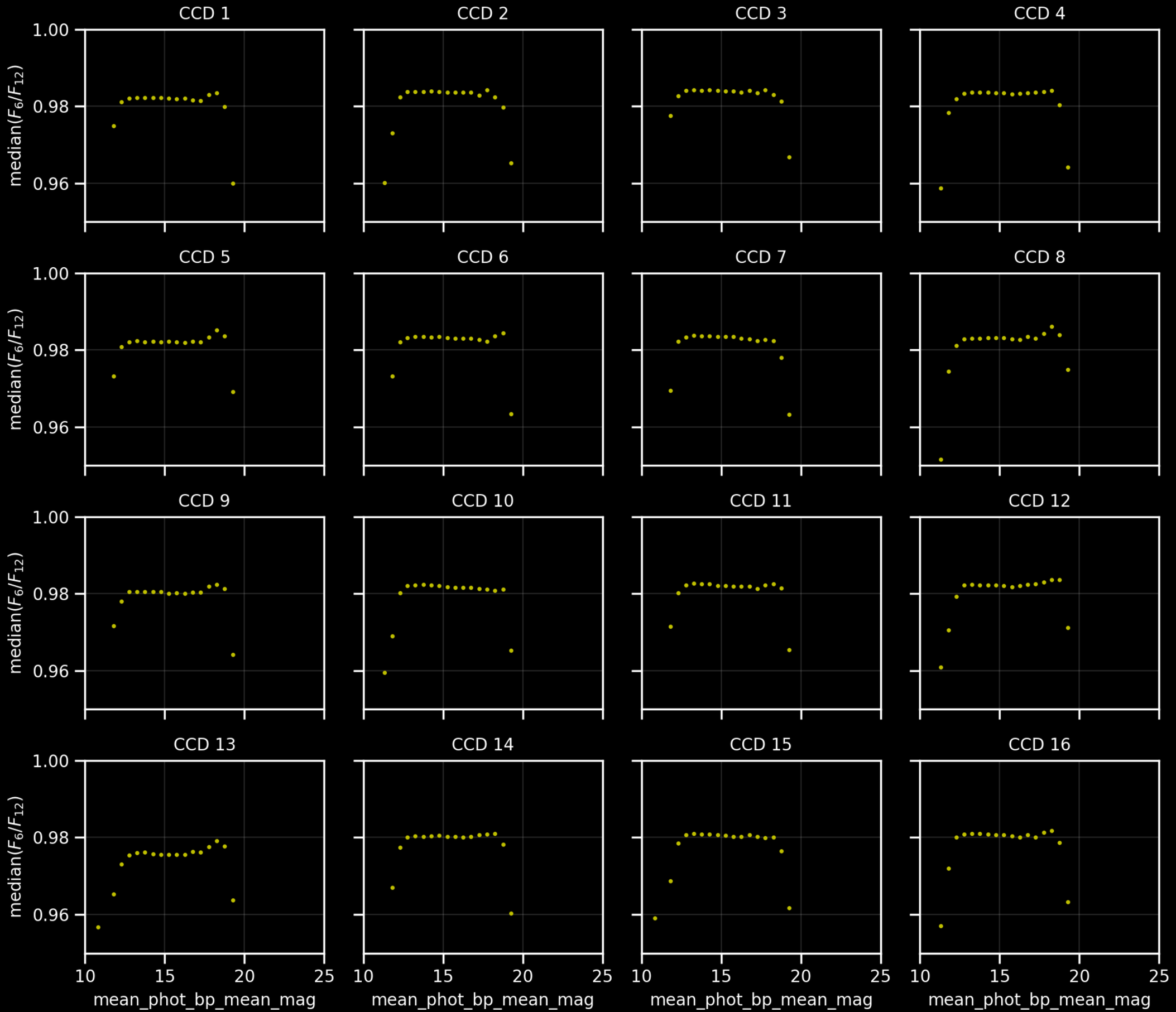
Aperture correction vs gaia bp | 2019 | ztf g

CCD 1
CCD 2
CCD 3
CCD 4
CCD 5
CCD 6
CCD 7
CCD 8
CCD 9
CCD 10
CCD 11
CCD 12
CCD 13
CCD 14
CCD 15
CCD 16

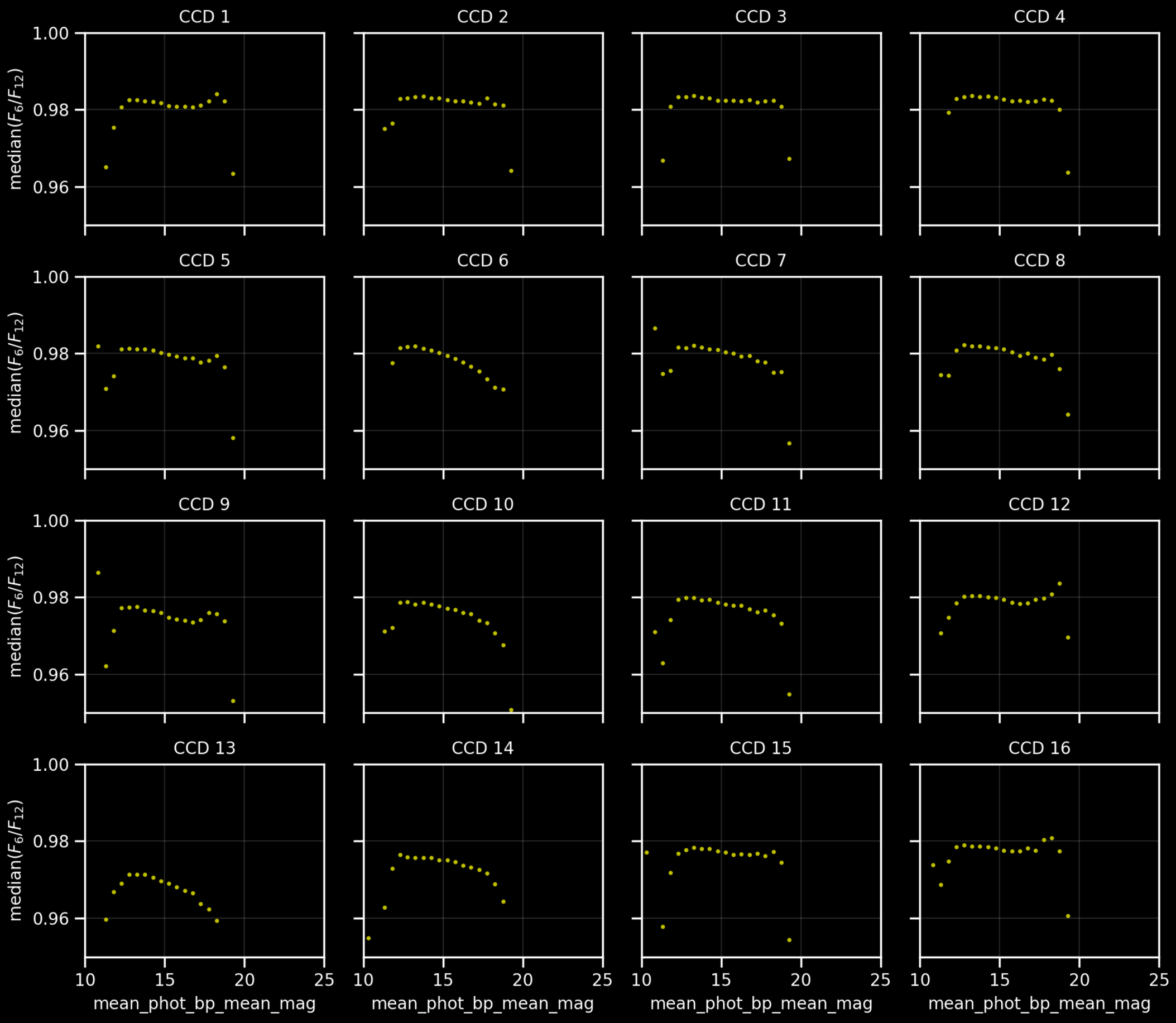
median(F_6/F_{12})
1.00
0.98
0.96

10
15
20
25
mean_phot_bp_mean_mag

Aperture correction vs gaia bp | date<2019-10-22 | ztf g



Aperture correction vs gaia bp | date>2019-10-22 | ztf g



Aperture correction vs gaia bp | date>2019-10-22 | ztf g

1.8<seeing < 2.1

CCD 1
CCD 2
CCD 3
CCD 4
CCD 5
CCD 6
CCD 7
CCD 8
CCD 9
CCD 10
CCD 11
CCD 12
CCD 13
CCD 14
CCD 15
CCD 16

median(F_6/F_{12})

1.00
0.98
0.96

10
15
20
25

mean_phot_bp_mean_mag

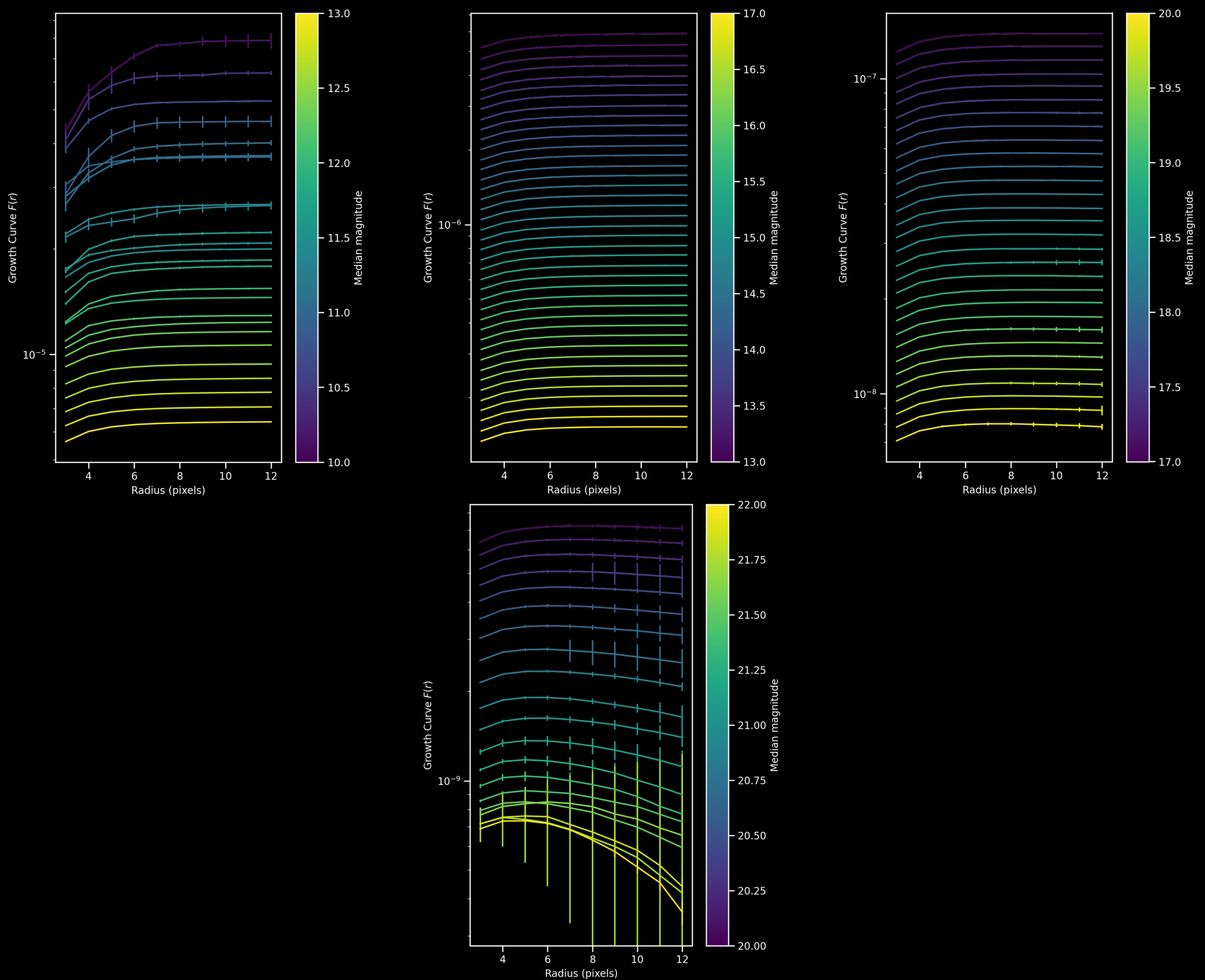
We run ubercal, get the total ZP, and correct a posteriori with a per expid mean term

per-exposure zero point correction

$$\delta Z_i = \left\langle m_{\mathrm{syn},s}(X=0) - m_{\mathrm{syn},s}(X=X_i) \right\rangle_s$$

$$m_{\mathrm{syn},s}(X) = -2.5 \log_{10} \frac{\int S_s(\lambda)\, T(\lambda)\, A(\lambda)^X\, \lambda\, d\lambda}{\int S_{AB}(\lambda)\, T(\lambda)\, A(\lambda)^X\, \lambda\, d\lambda}$$

$$\delta Z_i = \left\langle -2.5 \log_{10} \frac{\int S_s(\lambda)\, T(\lambda)\, \lambda\, d\lambda}{\int S_{AB}(\lambda)\, T(\lambda)\, \lambda\, d\lambda} + 2.5 \log_{10} \frac{\int S_s(\lambda)\, T(\lambda)\, A(\lambda)^{X_i}\, \lambda\, d\lambda}{\int S_{AB}(\lambda)\, T(\lambda)\, A(\lambda)^{X_i}\, \lambda\, d\lambda} \right\rangle_s$$


Growth Curve F(r)
Radius (pixels)
Median magnitude
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
4
6
8
10
12
13.0
12.5
12.0
11.5
11.0
10.5
10.0
17.0
16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
20.0
19.5
19.0
18.5
18.0
17.5
17.0
22.00
21.75
21.50
21.25
21.00
20.75
20.50
20.25
20.00

Aperture correction vs gaia bp | 2020 | ztf g

CCD 1
CCD 2
CCD 3
CCD 4
CCD 5
CCD 6
CCD 7
CCD 8
CCD 9
CCD 10
CCD 11
CCD 12
CCD 13
CCD 14
CCD 15
CCD 16

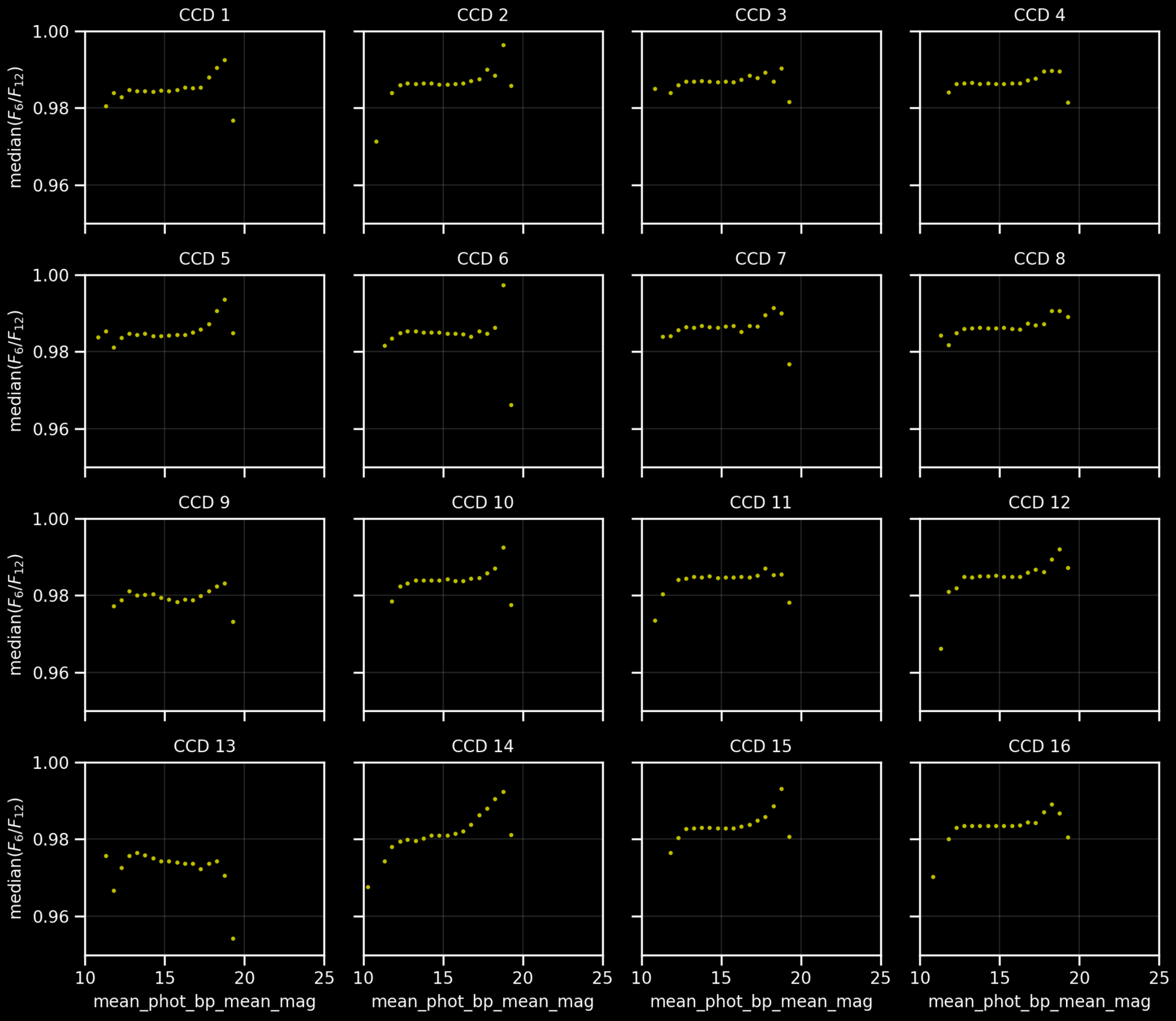
median(F_6/F_{12})

1.00
0.98
0.96

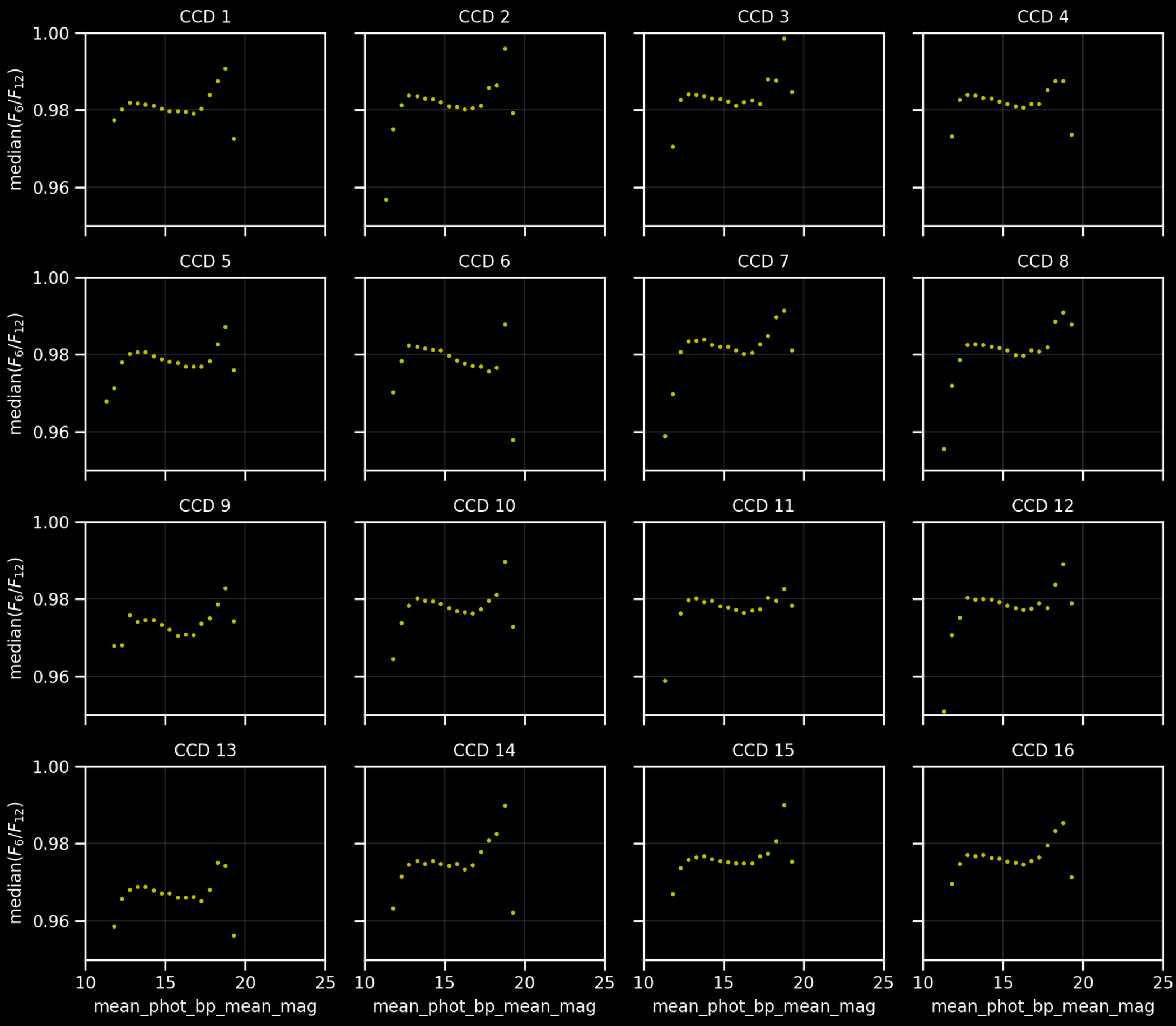
10
15
20
25

mean_phot_bp_mean_mag

Aperture correction vs gaia bp | date<2020-10-22 | ztf g



Aperture correction vs gaia bp | date>2020-10-22 | ztf g



Aperture correction vs gaia bp | 2020 | ztf g

1.8<seeing < 2.1

CCD 1 | CCD 2 | CCD 3 | CCD 4

CCD 5 | CCD 6 | CCD 7 | CCD 8

CCD 9 | CCD 10 | CCD 11 | CCD 12

CCD 13 | CCD 14 | CCD 15 | CCD 16

median(F_6/F_{12})

1.00

0.98

0.96

10 15 20 25

mean_phot_bp_mean_mag

Aperture correction vs gaia bp | date<2020-10-22 | ztf g

1.8<seeing < 2.1

CCD 1

CCD 2

CCD 3

CCD 4

CCD 5

CCD 6

CCD 7

CCD 8

CCD 9

CCD 10

CCD 11

CCD 12

CCD 13

CCD 14

CCD 15

CCD 16

median(F_6/F_{12})

1.00

0.98

0.96

10

15

20

25

mean_phot_bp_mean_mag

Aperture correction vs gaia bp | date>2020-10-22 | ztf g

1.8<seeing < 2.1

CCD 1

CCD 2

CCD 3

CCD 4

CCD 5

CCD 6

CCD 7

CCD 8

CCD 9

CCD 10

CCD 11

CCD 12

CCD 13

CCD 14

CCD 15

CCD 16

median(F_6/F_{12})

1.00

0.98

0.96

10

15

20

25

mean_phot_bp_mean_mag