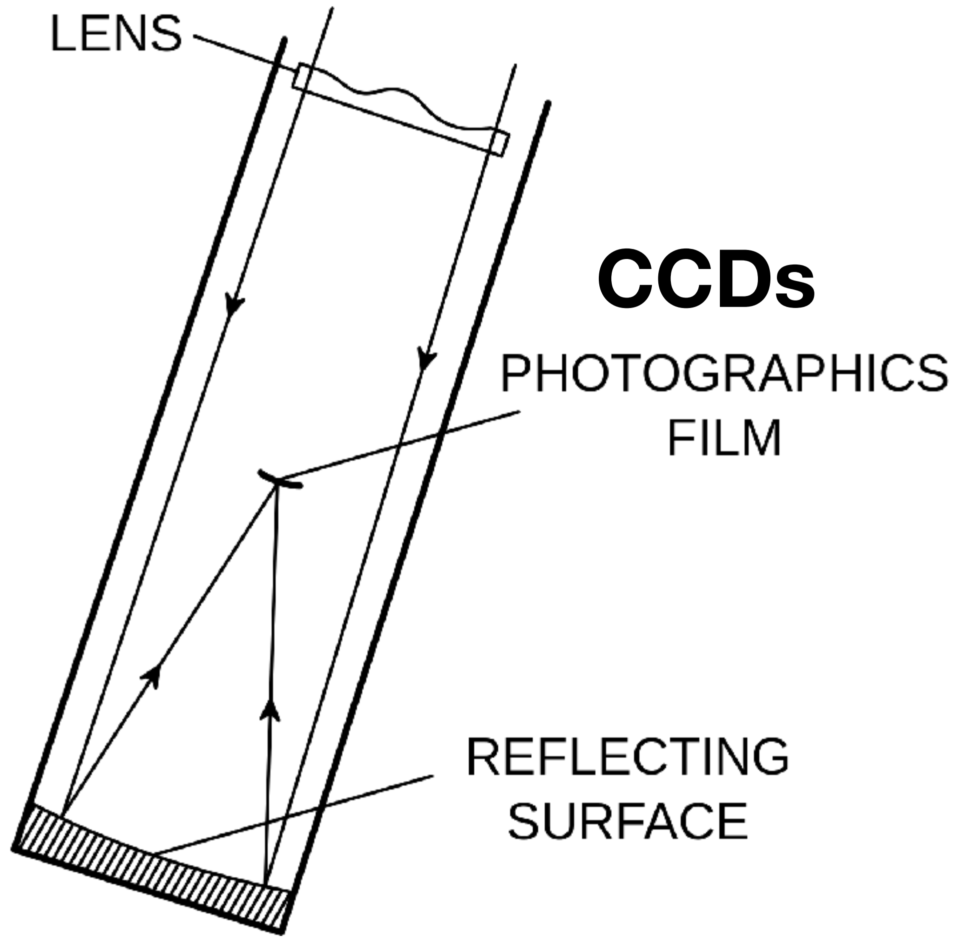
Ubercal for ZTF

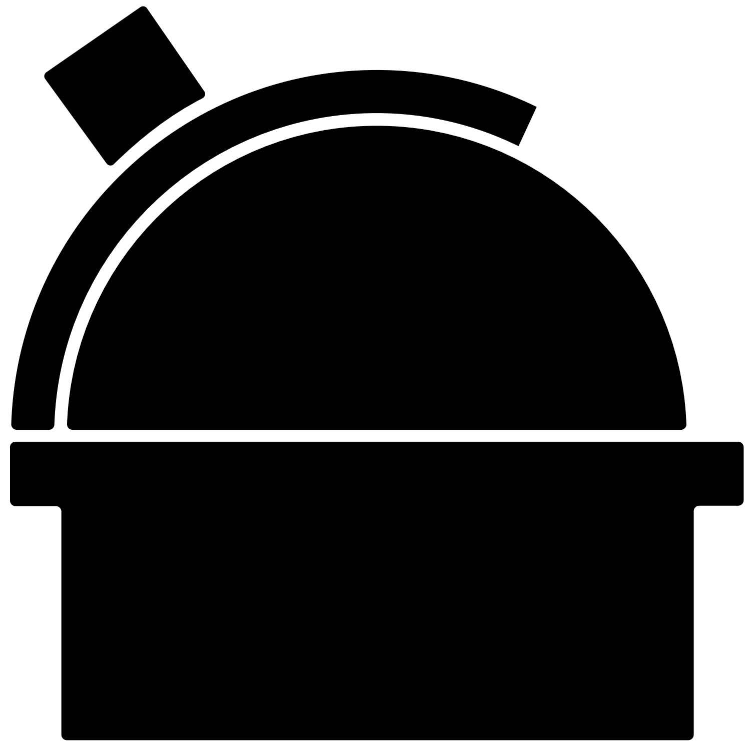
Benjamin Racine & Fabrice Feinstein

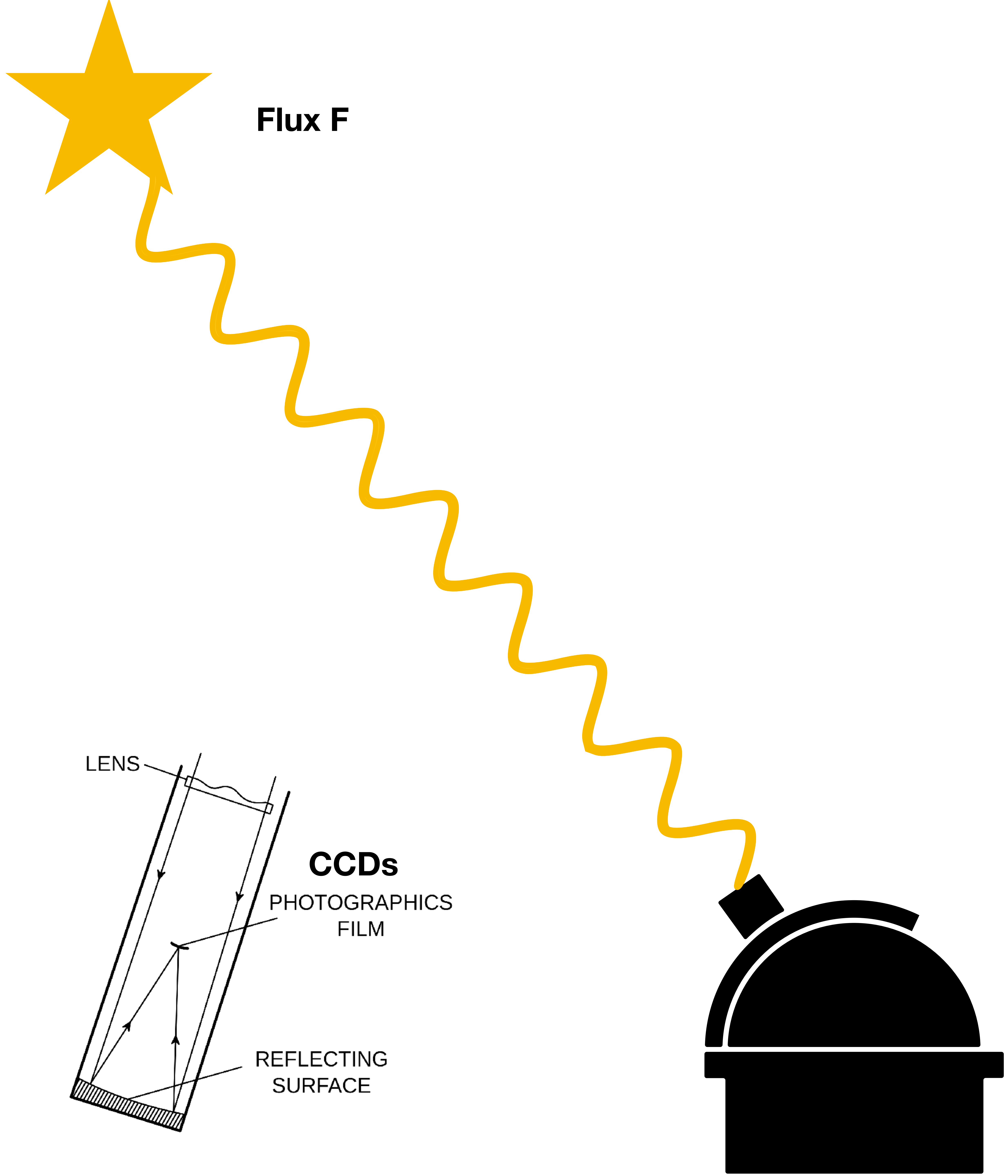
November 23rd, 2021

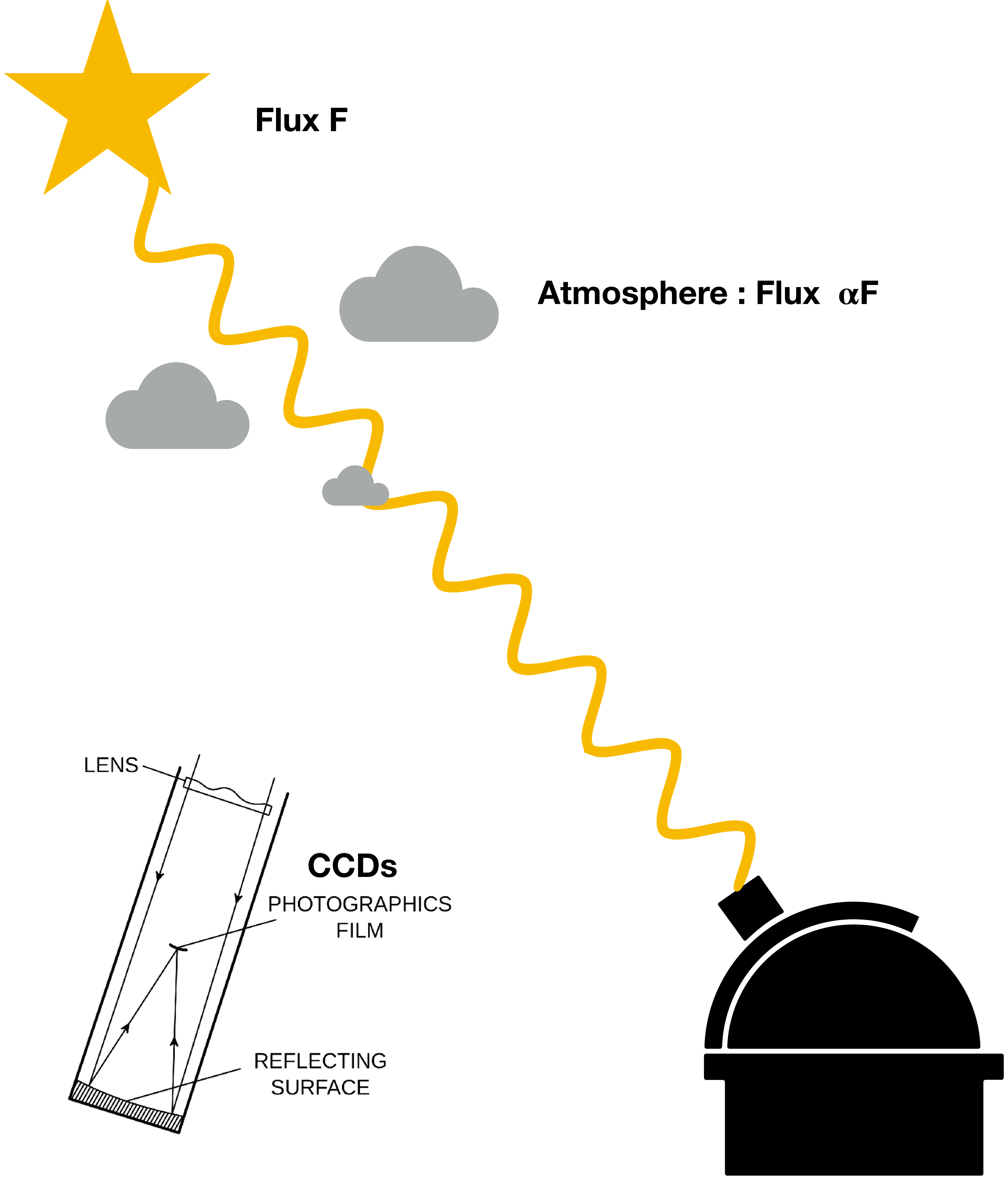
Flux F



CCDs




Flux F
LENS
CCDs
PHOTOGRAPHICS
FILM
REFLECTING
SURFACE


Flux F
Atmosphere : Flux αF
LENS
CCDs
PHOTOGRAPHICS
FILM
REFLECTING
SURFACE


Flux F
Atmosphere : Flux αF
Instrument
LENS
CCDs
PHOTOGRAPHICS
FILM
REFLECTING
SURFACE


Flux F
Atmosphere : Flux αF
Instrument
Mirrors etc. : Flux αβF
LENS
CCDs
PHOTOGRAPHICS
FILM
REFLECTING
SURFACE


Flux F
Atmosphere : Flux αF
LENS
CCDs
PHOTOGRAPHICS
FILM
REFLECTING
SURFACE
Instrument
Mirrors etc. : Flux αβF
Filters : Flux αβγF

Flux F
Atmosphere : Flux αF
Instrument
Mirrors etc. : Flux αβF
Filters : Flux αβγF
Detectors : Flux αβγδF
LENS
CCDs
PHOTOGRAPHICS FILM
REFLECTING SURFACE

Flux F
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Filters : Flux αβγF
Detectors : Flux αβγδF
Amplifiers : Flux αβγδεF
+V
-V


Flux F
Atmosphere : Flux αF
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REFLECTING SURFACE
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Amplifiers : Flux αβγδεF
+V
-V
Signal measured in ADU

Flux F
Atmosphere : Flux αF
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Detectors : Flux αβγδF
Amplifiers : Flux αβγδεF
+V
-V
-
+
Signal
measured
in ADU
$m_{meas} = -2.5 \log (F_{meas})$
$= -2.5 \log (F) - 2.5 \log (\alpha\beta\gamma\delta\epsilon)$


Flux F
Atmosphere : Flux αF
LENS
CCDs
PHOTOGRAPHICS FILM
REFLECTING SURFACE
Instrument
Mirrors etc. : Flux αβF
Filters : Flux αβγF
Detectors : Flux αβγδF
Amplifiers : Flux αβγδεF
+V
-V
Signal measured in ADU
$m_{meas} = -2.5 \log (F_{meas})$
$= -2.5 \log (F) - 2.5 \log (\alpha\beta\gamma\delta\epsilon)$
ZP

Flux F
Depends on time, elevation etc
Atmosphere : Flux αF
LENS
CCDs
PHOTOGRAPHICS
FILM
REFLECTING
SURFACE
Instrument
Dust spots? Aging?
Mirrors etc. : Flux αβF
Dust? Frequency dependence of course
Filters : Flux αβγF
Edges, dust, coating etc.
Detectors : Flux αβγδF
Gain variations etc?
Amplifiers : Flux αβγδεF
+V
-V
Signal measured in ADU
$m_{meas} = -2.5 \log (F_{meas})$
$= -2.5 \log (F) - 2.5 \log (\alpha\beta\gamma\delta\epsilon)$
ZP

$$m_{calib} = -2.5 \log (F)$$
$$= -2.5 \log (F_{meas}) + ZP$$

in ADU/s

The zeropoint is the magnitude corresponding to a flux of 1 ADU/s

Current photometry

For each filter (g,r,i) :

$$m_{cal} = m_{inst} + ZP$$

Varies with time, airmass, position on Focal plane etc.

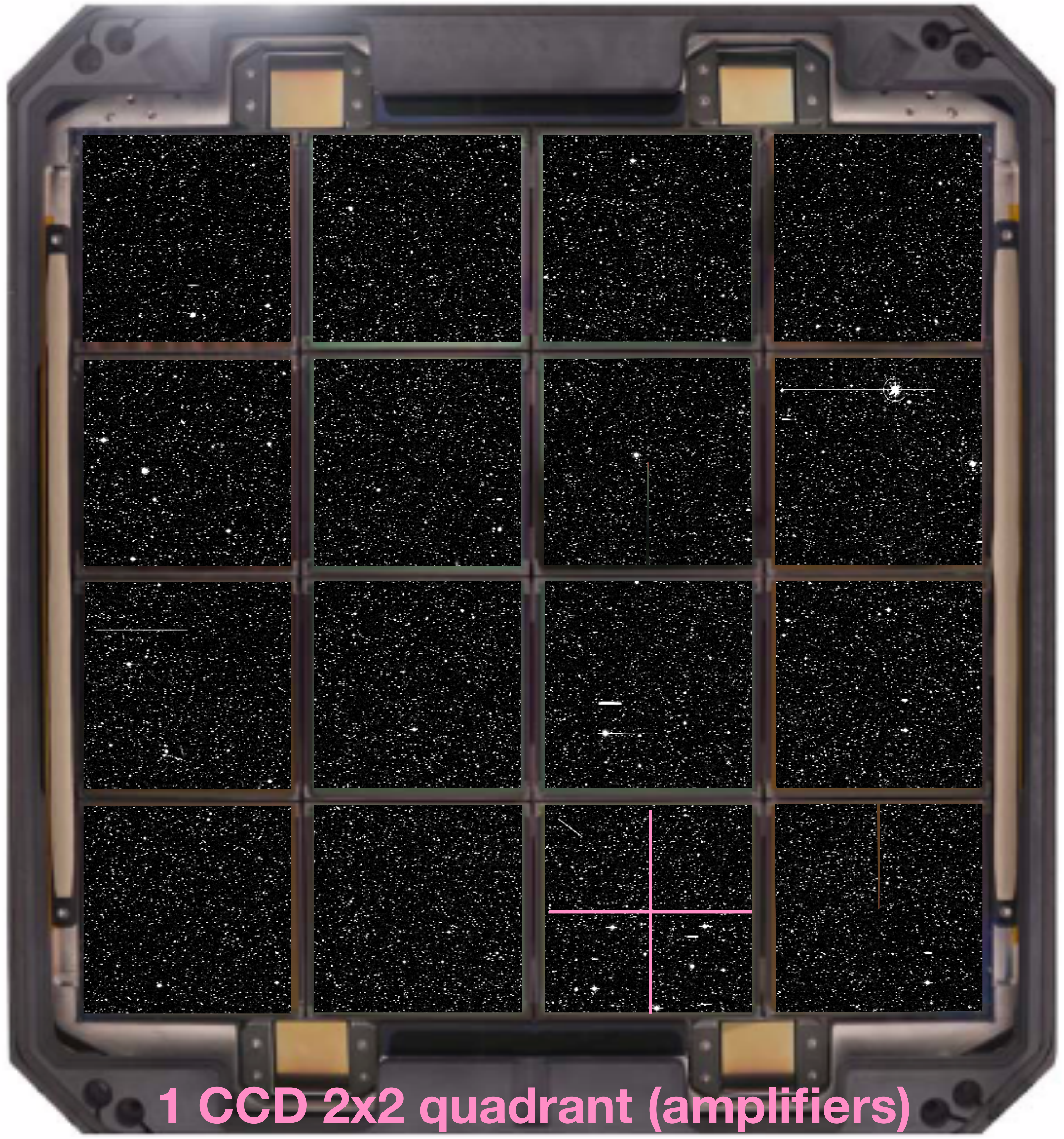
ZTF Focal Plane: 4x4 CCD

ZP Calibrated, by quadrant, against PS1

~1 (2?) % reproducibility (stars)

Current photometry

ZTF Focal Plane: 4x4 CCD



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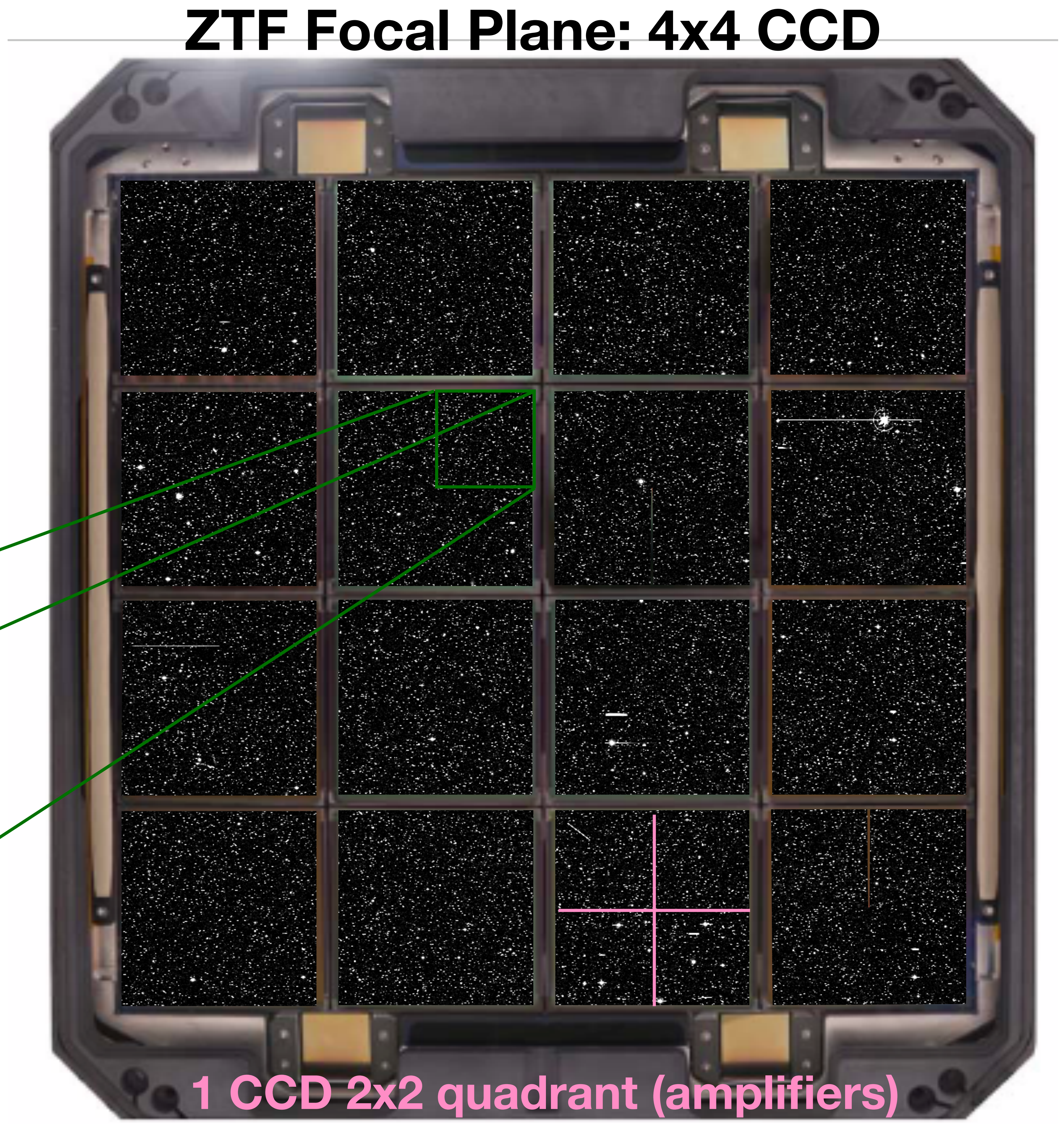

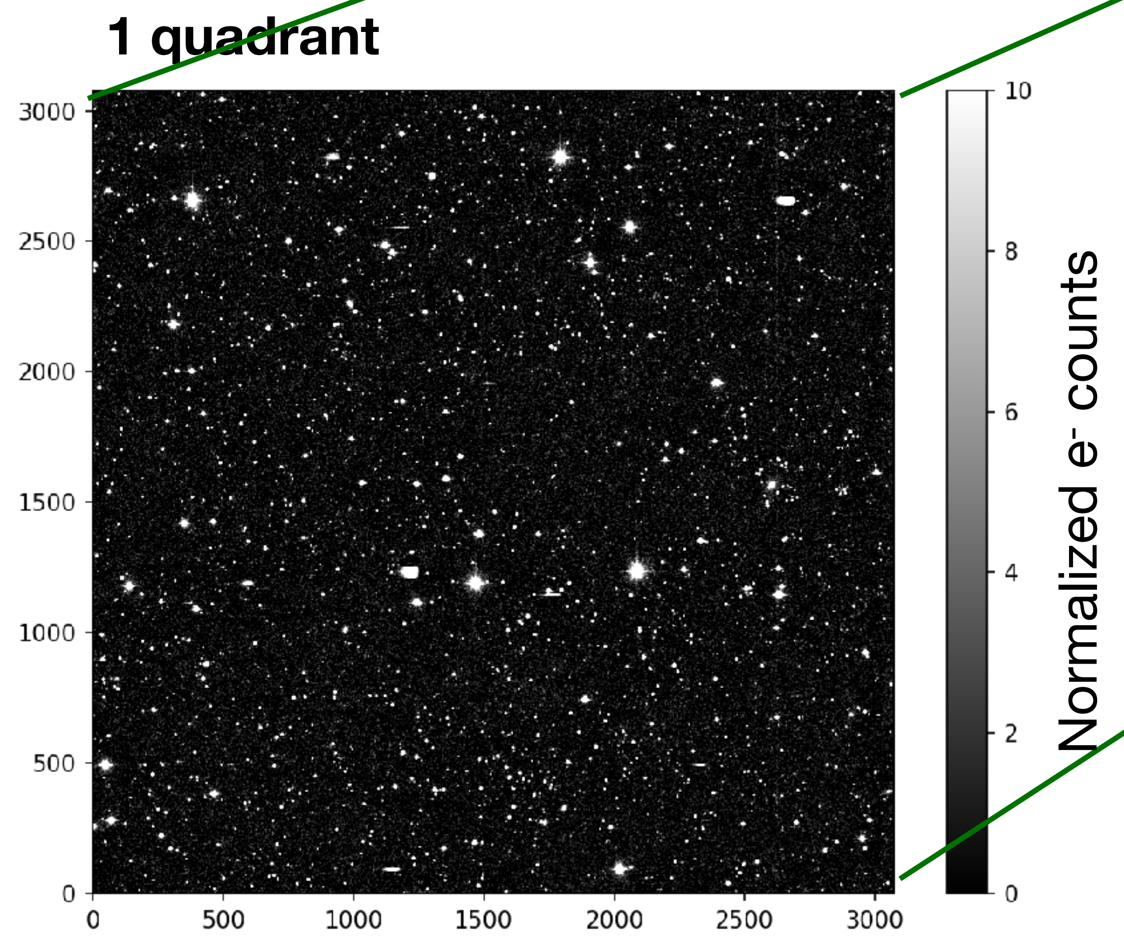

ZP Calibrated, by quadrant, against PS1

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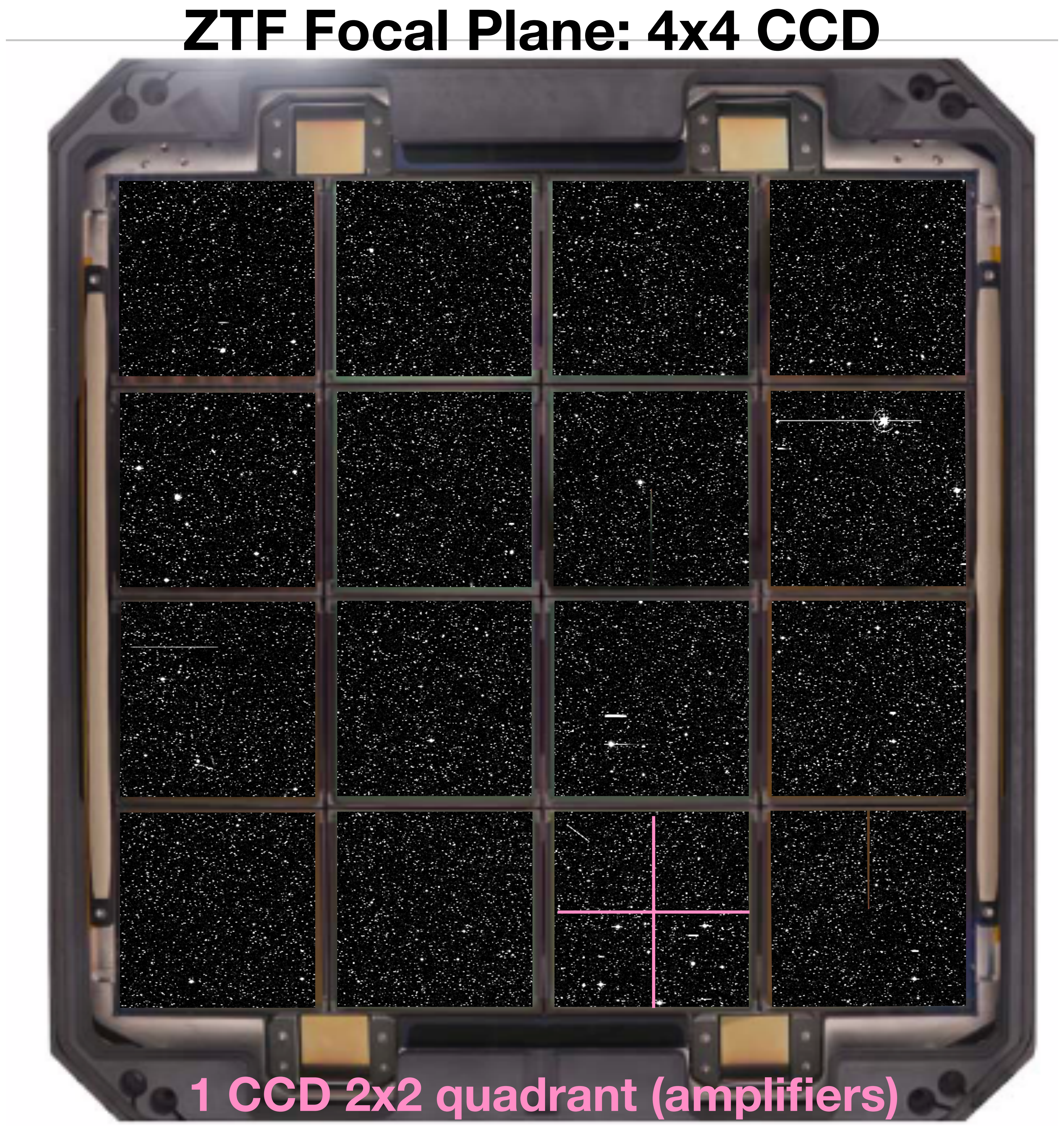
Current photometry

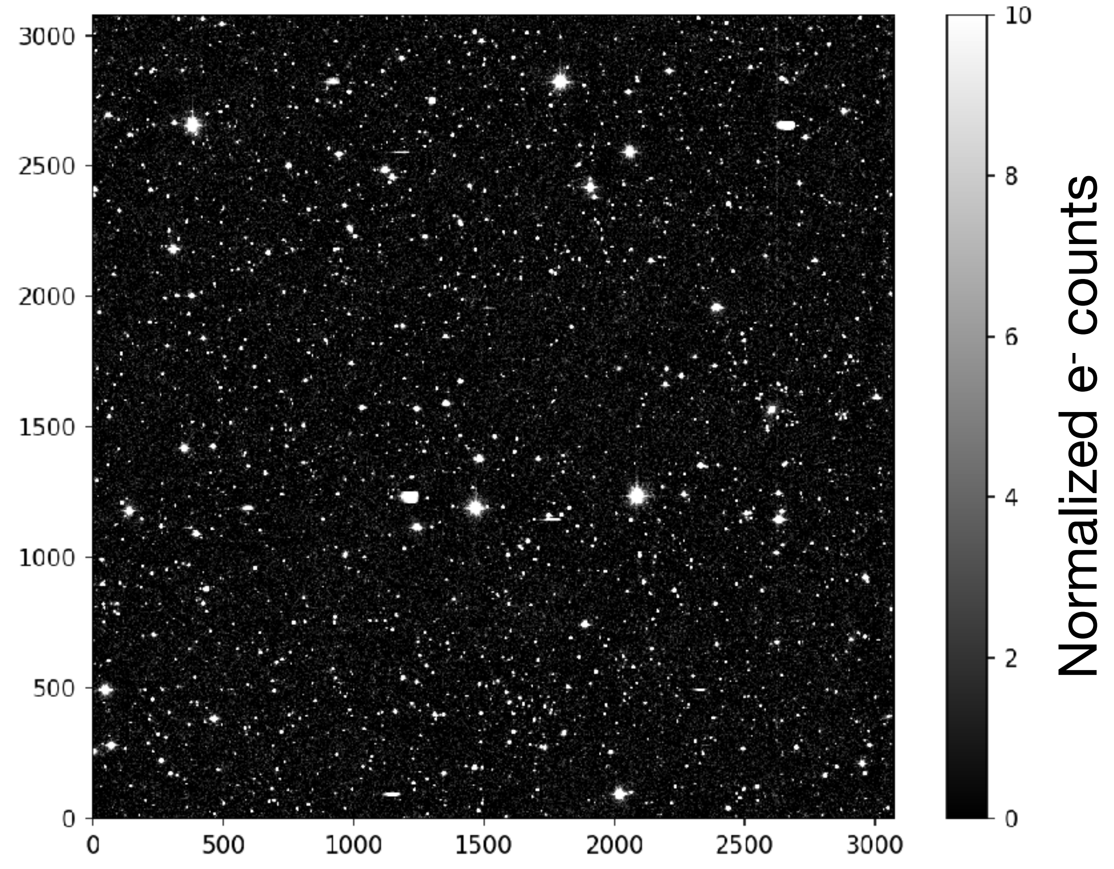


For each filter (g,r,i) :

$$m_{cal} = m_{inst} + ZP$$

Varies with time, airmass, position on Focal plane etc.

1 quadrant

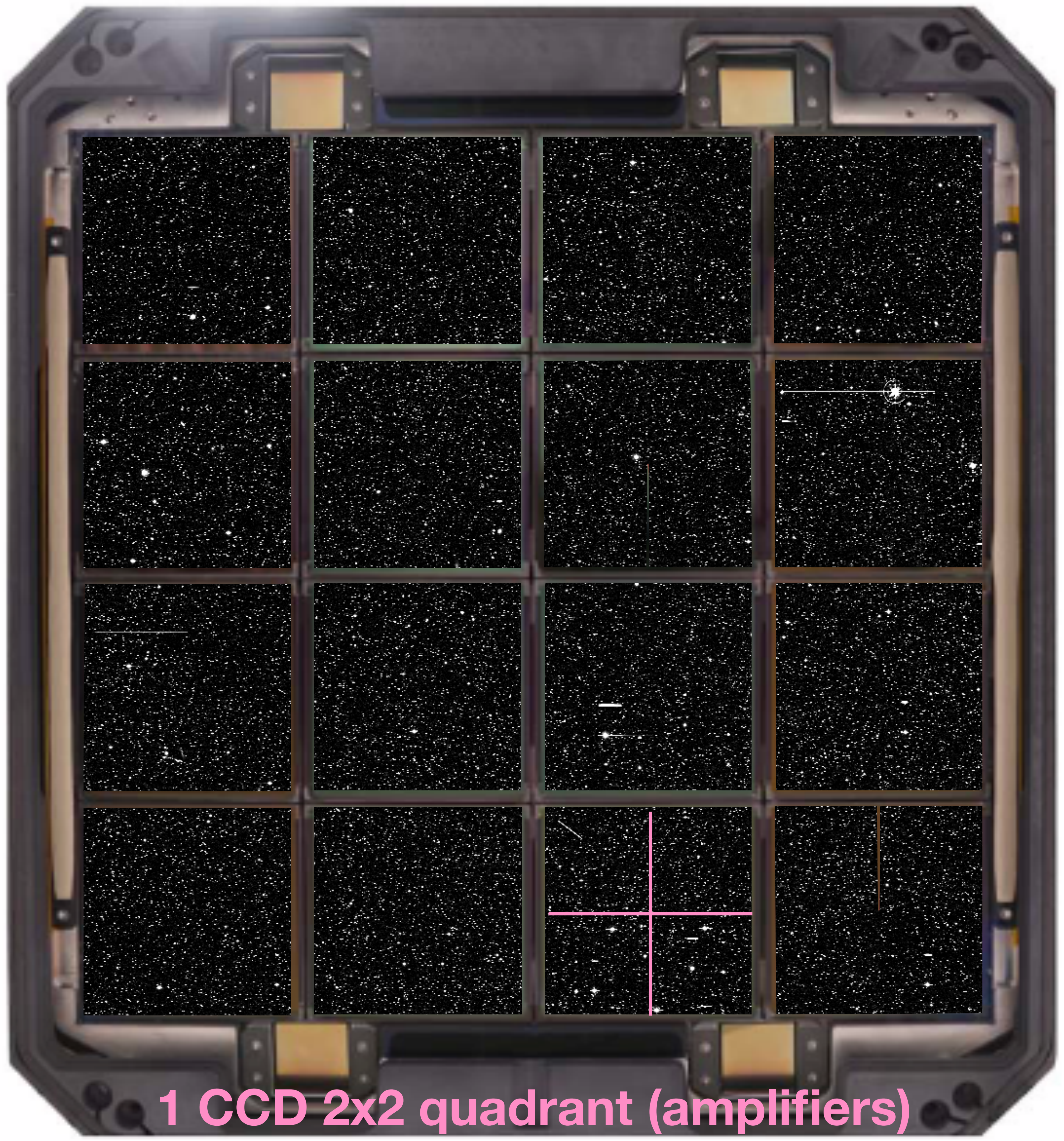


ZP Calibrated, by quadrant, against PS1

~1 (2?) % reproducibility (stars)

Current photometry

ZTF Focal Plane: 4x4 CCD

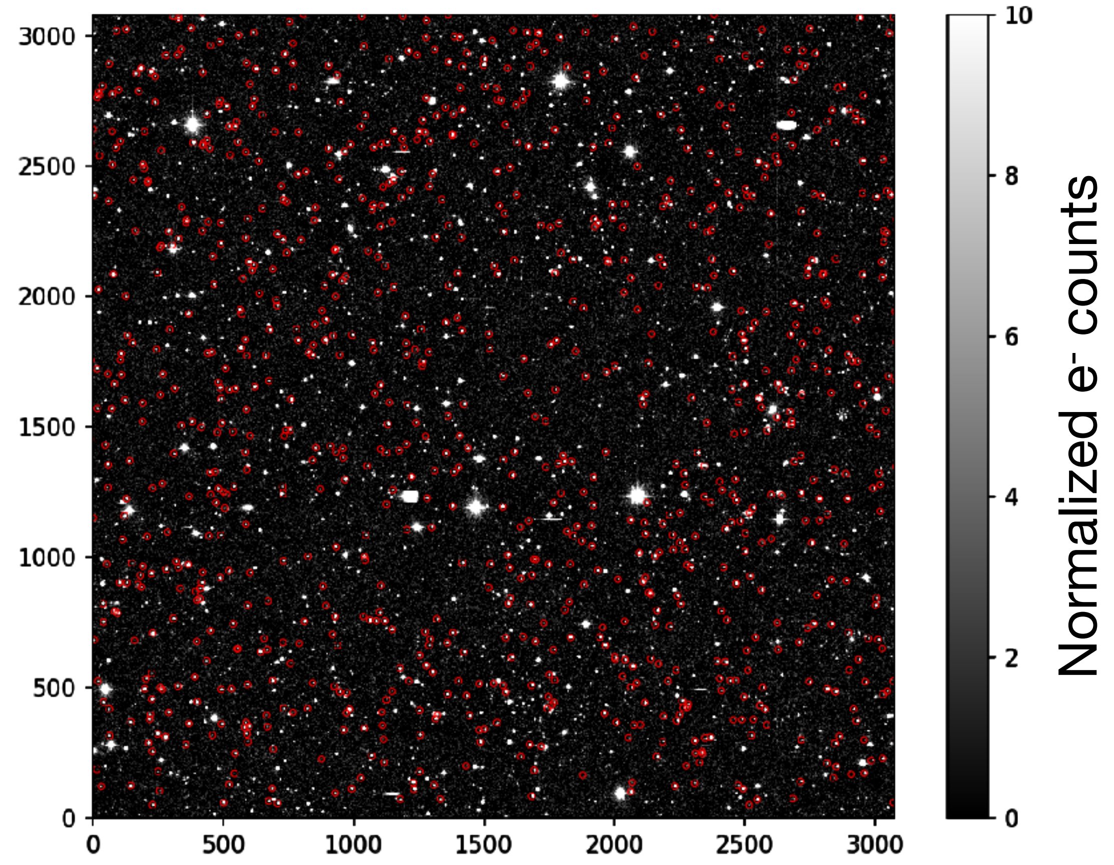


For each filter (g,r,i) :

$$m_{cal} = m_{inst} + ZP$$

Varies with time, airmass, position on Focal plane etc.

1 quadrant + Panstarr calibrators



ZP Calibrated, by quadrant, against PS1

~1 (2?) % reproducibility (stars)

Current photometry

For each filter (g,r,i) :

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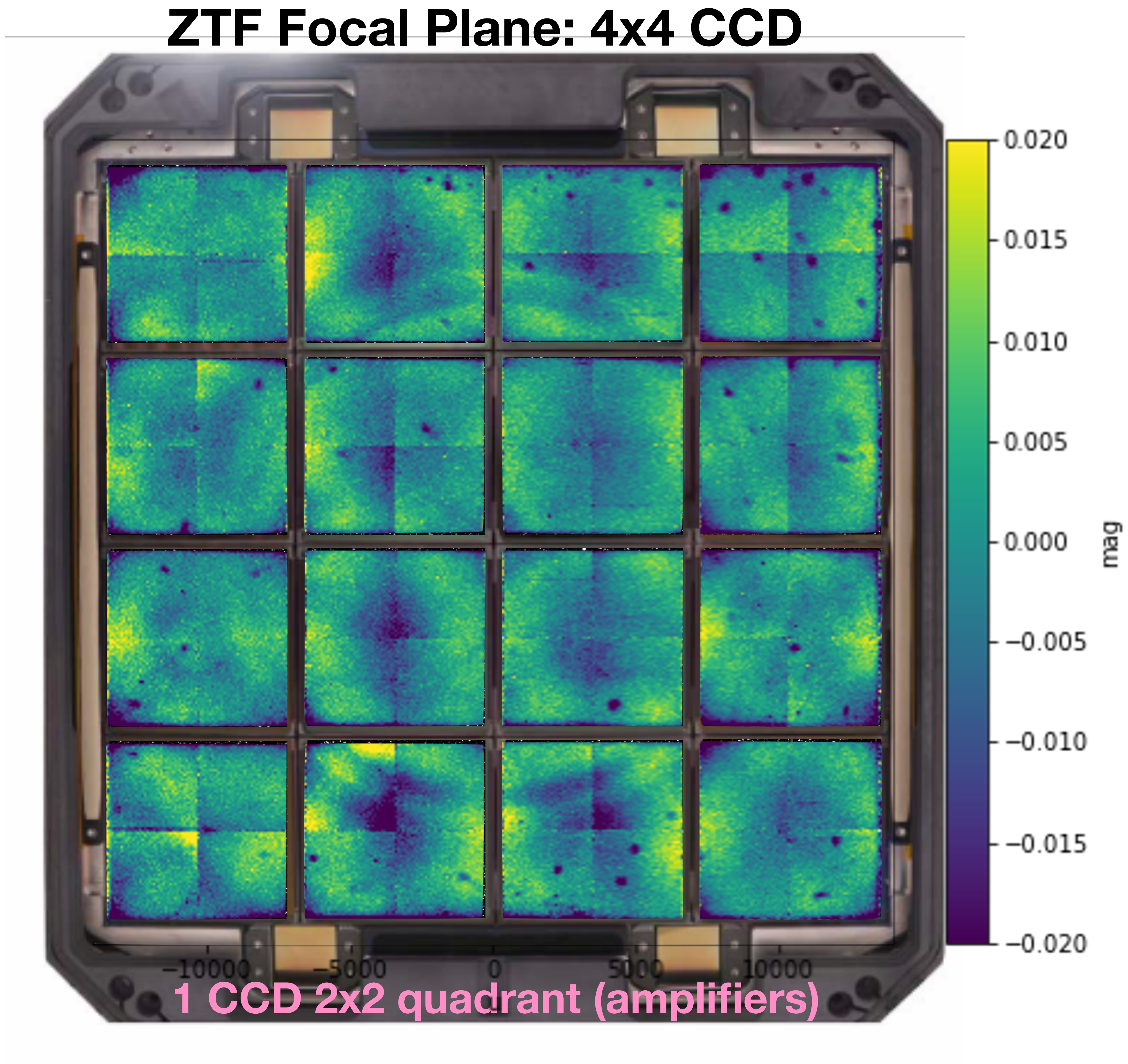
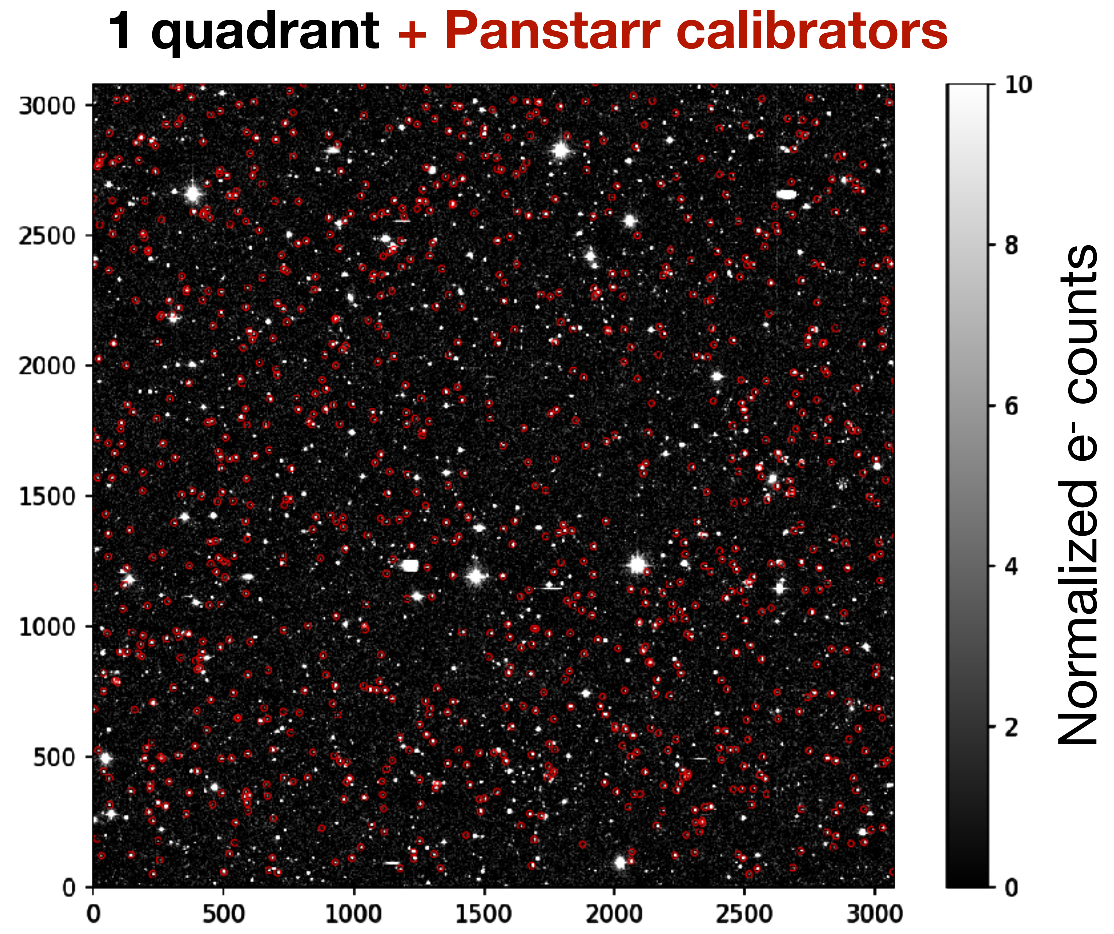
Varies with time, airmass, position on Focal plane etc.





ZP Calibrated, by quadrant, against PS1

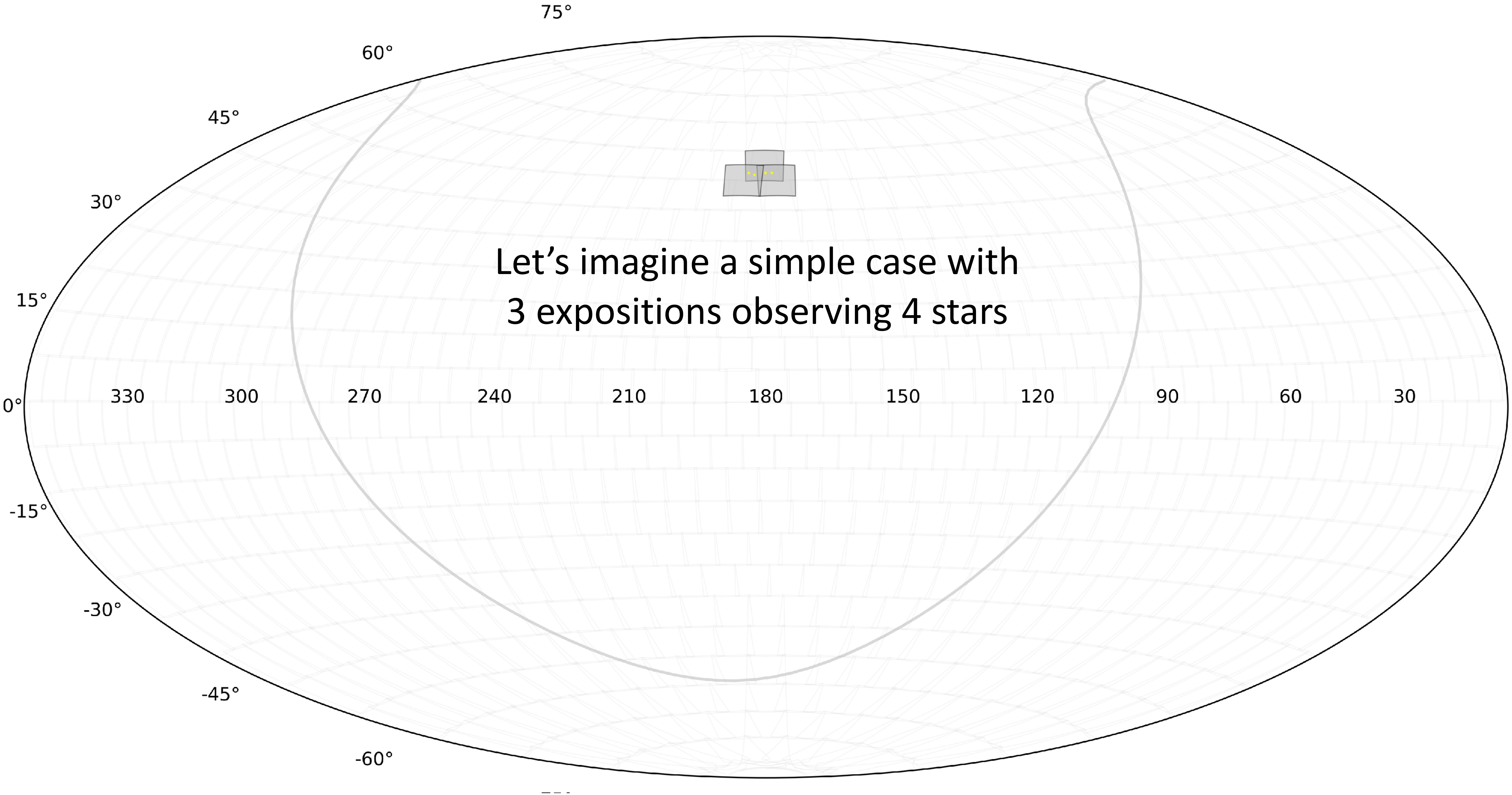
~1 (2?) % reproducibility (stars)

Ubercal method for ZTF

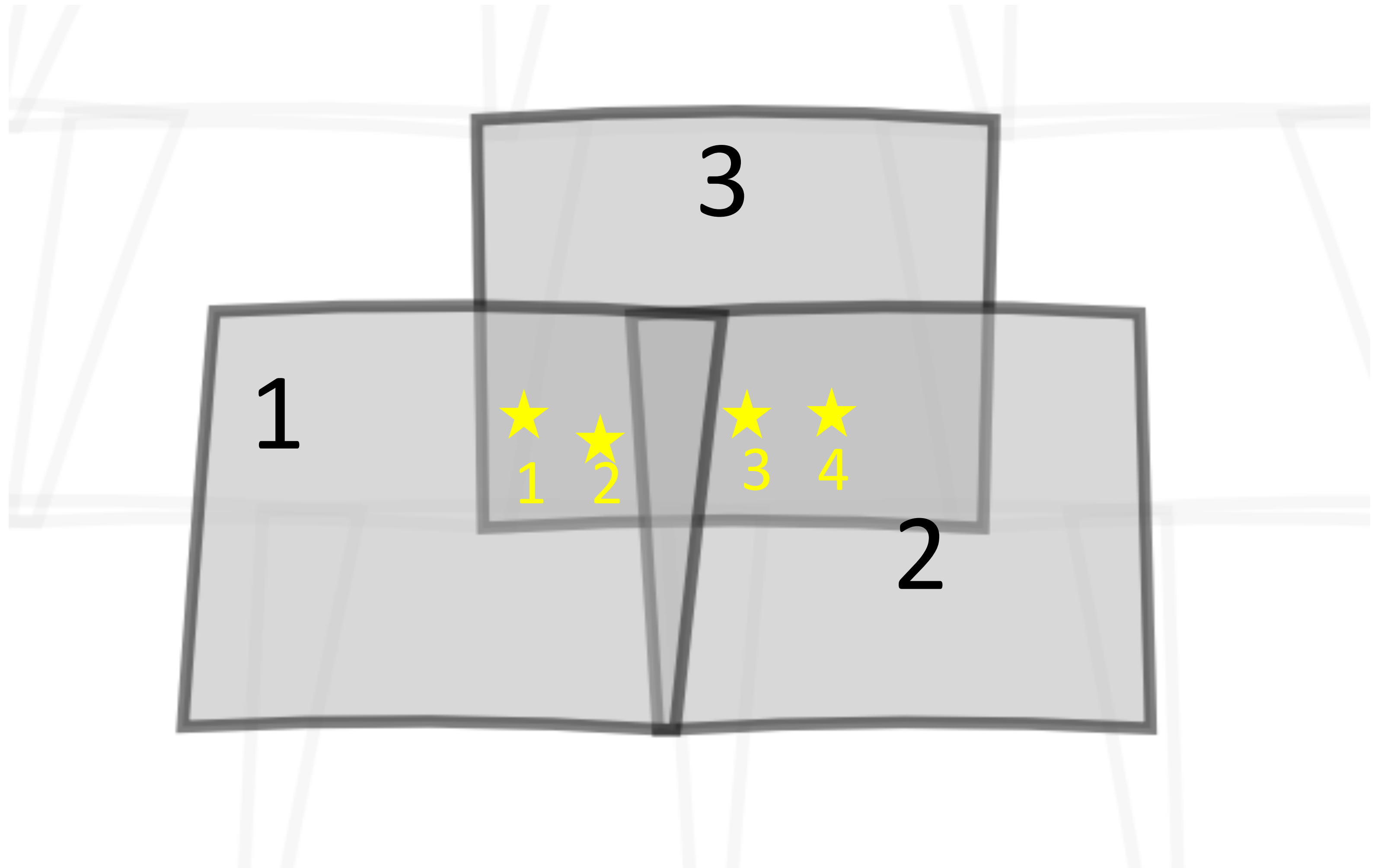
What is it ?
A global least-square linear fit of:
- star magnitudes
- instrument parameters (Focal plane Zero Points variations, …)
- atmosphere attenuation : (non-) grey extinction (clouds, dust, …)

Why use it ?
Well tested method (see Padmanaban et al.) developed for SDSS
Self-consistent relative auto-calibration
Use of fast and robust sparse matrix algorithms (Cholesky decomposition…)
The more data you incorporate, the better the calibration is —> goal is O(mmag) !!

How do we proceed ?
Use of algorithms developed on LSST cadence and GAIA sky simulations
We started to test the method on existing PSF-photometry ZTF catalogs



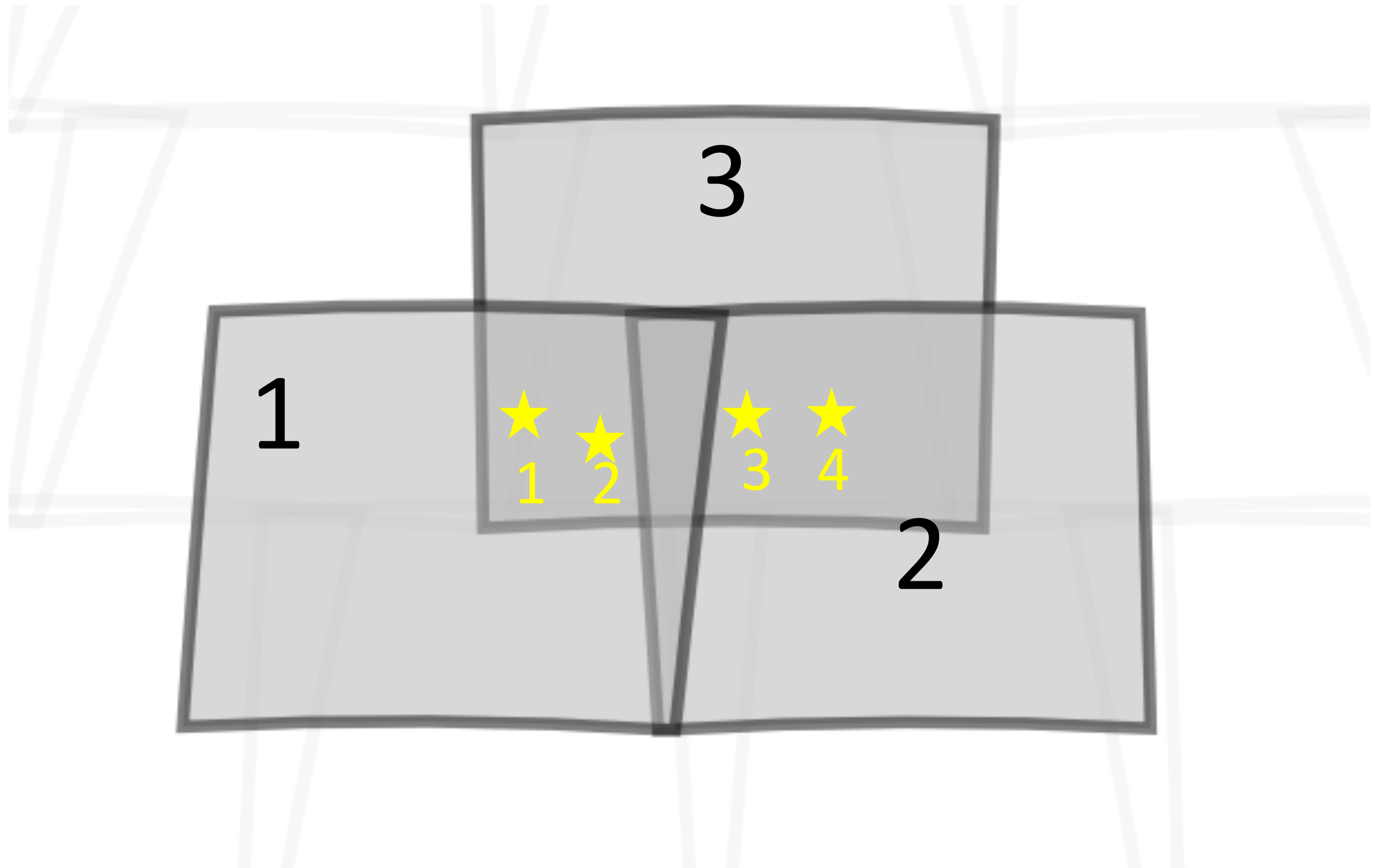
Let’s imagine a simple case with
3 expositions observing 4 stars



Ubercal method

$$m_{i_{star}} + ZP_{j_{field}} = m^{obs}_{i_{star},\, j_{field}}$$

$$m_1 + ZP_1 = m^{obs}_{11}$$
$$m_2 + ZP_1 = m^{obs}_{21}$$
$$m_3 + ZP_2 = m^{obs}_{32}$$
$$m_4 + ZP_2 = m^{obs}_{42}$$
$$m_1 + ZP_3 = m^{obs}_{13}$$
$$m_2 + ZP_3 = m^{obs}_{23}$$
$$m_3 + ZP_3 = m^{obs}_{33}$$
$$m_4 + ZP_3 = m^{obs}_{43}$$

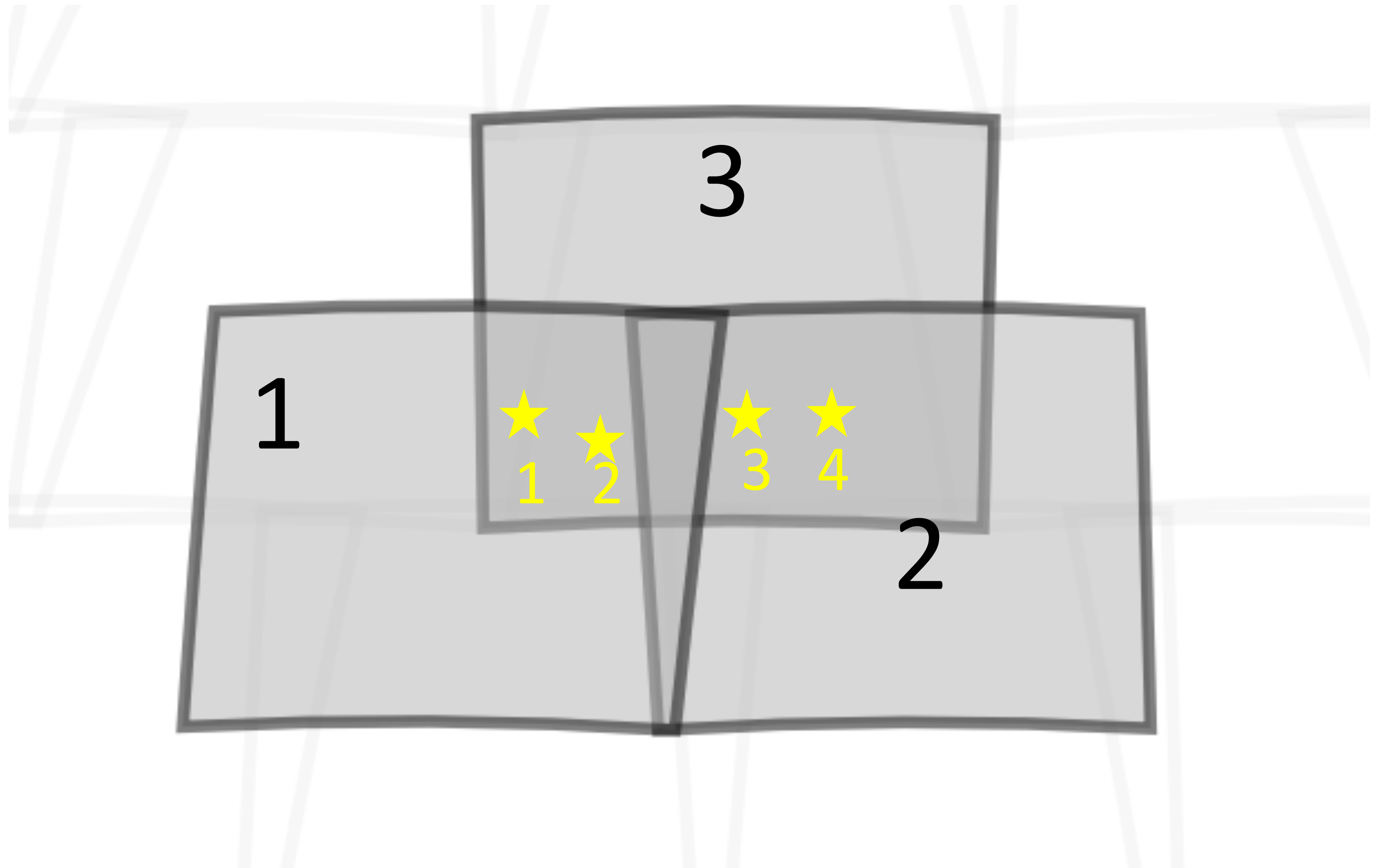


Ubercal method

$$m_{i_{star}} + ZP_{j_{field}} = m^{obs}_{i_{star}, j_{field}}$$

$$m_1 + ZP_1 = m^{obs}_{11}$$
$$m_2 + ZP_1 = m^{obs}_{21}$$
$$m_3 + ZP_2 = m^{obs}_{32}$$
$$m_4 + ZP_2 = m^{obs}_{42}$$
$$m_1 + ZP_3 = m^{obs}_{13}$$
$$m_2 + ZP_3 = m^{obs}_{23}$$
$$m_3 + ZP_3 = m^{obs}_{33}$$
$$m_4 + ZP_3 = m^{obs}_{43}$$

absolute mag / ZP not constrained
=> fit of relative ZPs

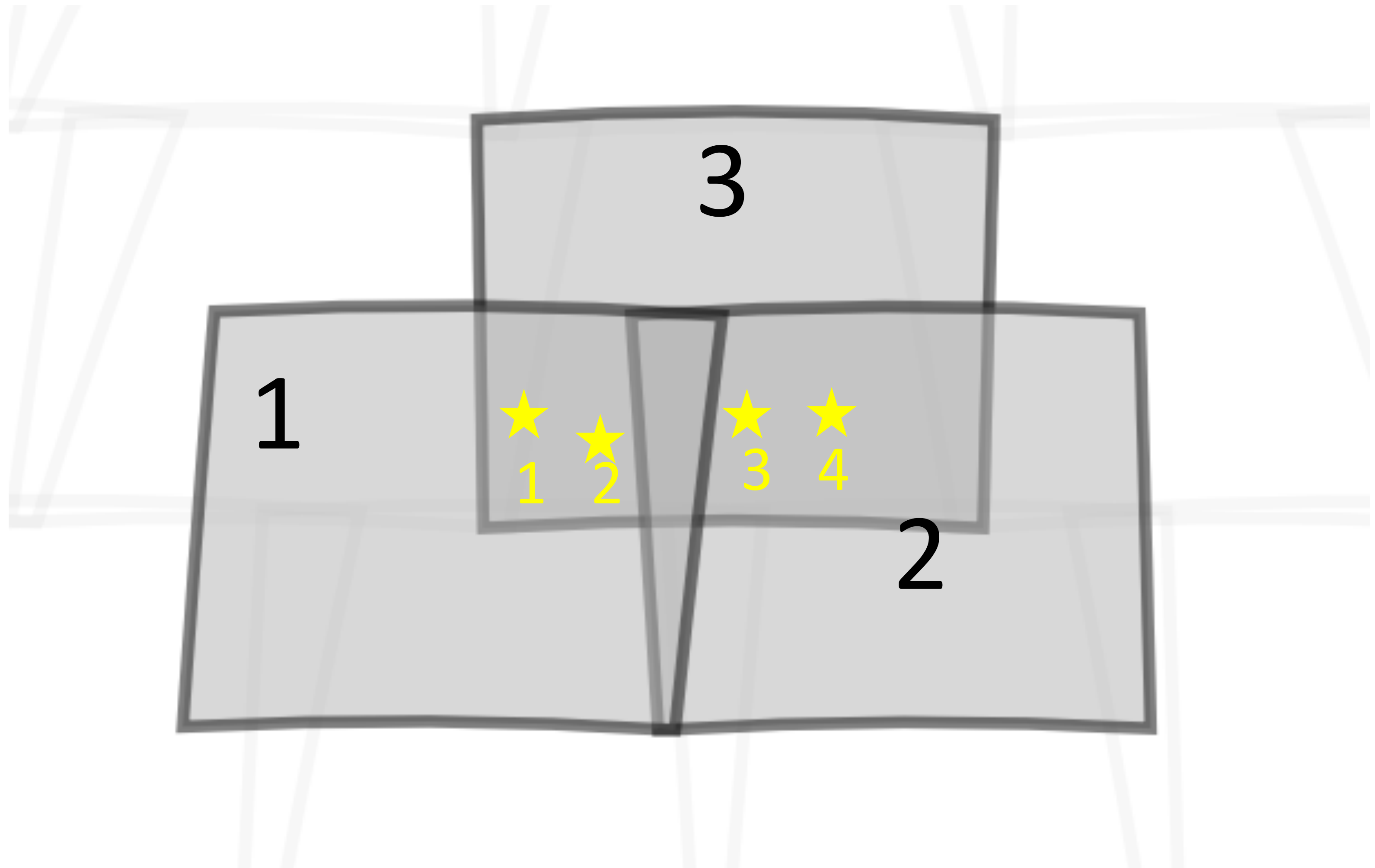


Ubercal method

$$m_{i_{star}} + ZP_{j_{field}} = m^{obs}_{i_{star},\, j_{field}}$$

$$m_1 + 0 = m^{obs}_{11}$$
$$m_2 + 0 = m^{obs}_{21}$$
$$m_3 + \Delta ZP_2 = m^{obs}_{32}$$
$$m_4 + \Delta ZP_2 = m^{obs}_{42}$$
$$m_1 + \Delta ZP_3 = m^{obs}_{13}$$
$$m_2 + \Delta ZP_3 = m^{obs}_{23}$$
$$m_3 + \Delta ZP_3 = m^{obs}_{33}$$
$$m_4 + \Delta ZP_3 = m^{obs}_{43}$$

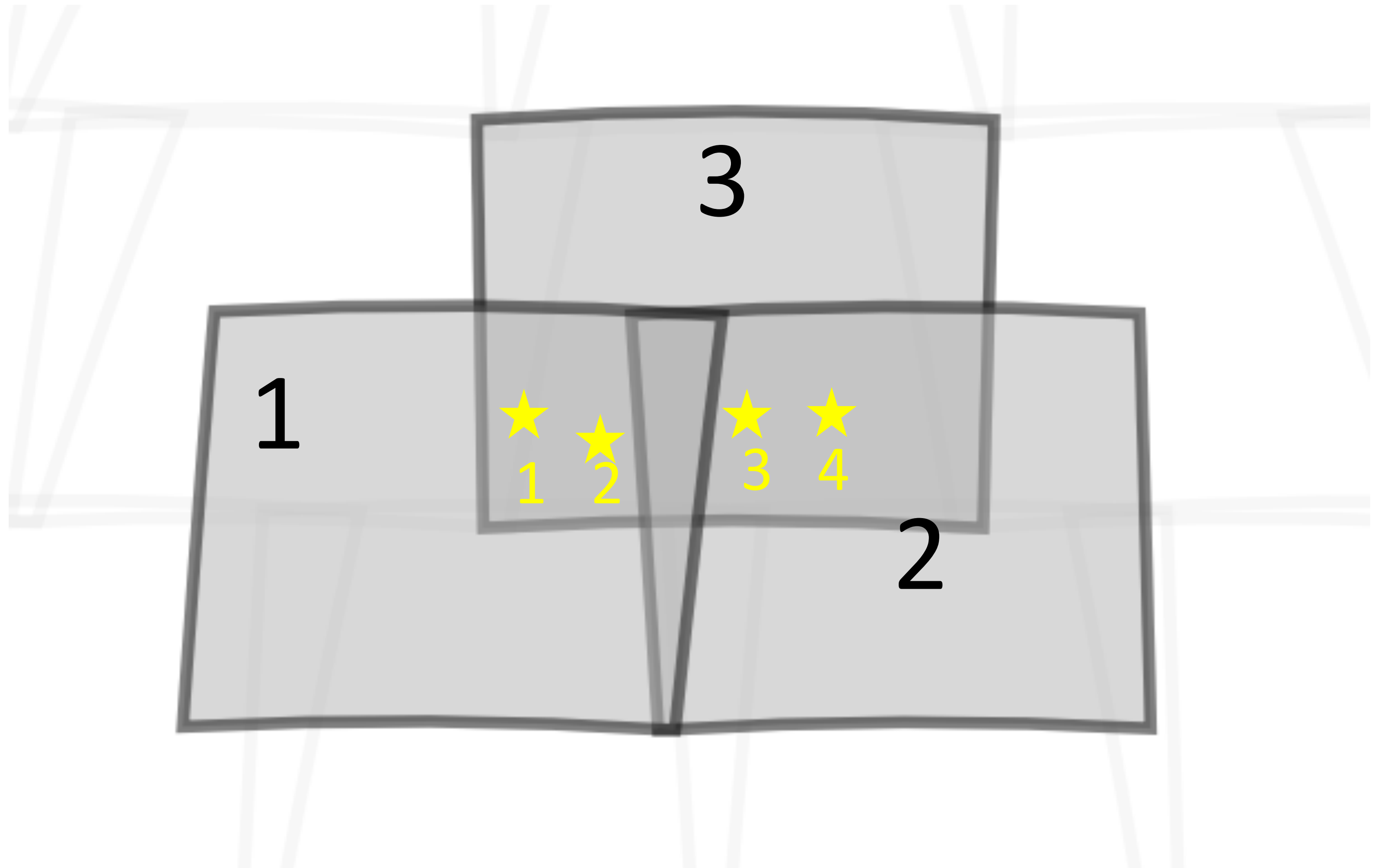
Degenerate problem !



Ubercal method

$$
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 & 1 & 0 \\
1 & 0 & 0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 1
\end{bmatrix}
\cdot
\begin{bmatrix}
m_1 \\ m_2 \\ m_3 \\ m_4 \\ \Delta ZP_2 \\ \Delta ZP_3
\end{bmatrix}
=
\begin{bmatrix}
m_{11}^{obs} \\ m_{21}^{obs} \\ m_{32}^{obs} \\ m_{42}^{obs} \\ m_{13}^{obs} \\ m_{23}^{obs} \\ m_{33}^{obs} \\ m_{43}^{obs}
\end{bmatrix}
$$

$$
A_{8x6} \cdot X_{6x1} = B_{8x1}
$$



Ubercal method

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \\ \Delta ZP_2 \\ \Delta ZP_3 \end{bmatrix} = \begin{bmatrix} m_{11}^{obs} \\ m_{21}^{obs} \\ m_{32}^{obs} \\ m_{42}^{obs} \\ m_{13}^{obs} \\ m_{23}^{obs} \\ m_{33}^{obs} \\ m_{43}^{obs} \end{bmatrix}$$

$$A_{8x6} \cdot X_{6x1} = B_{8x1}$$

system of 8 equations :

$A\,X = B$

<u>least square fit</u> :

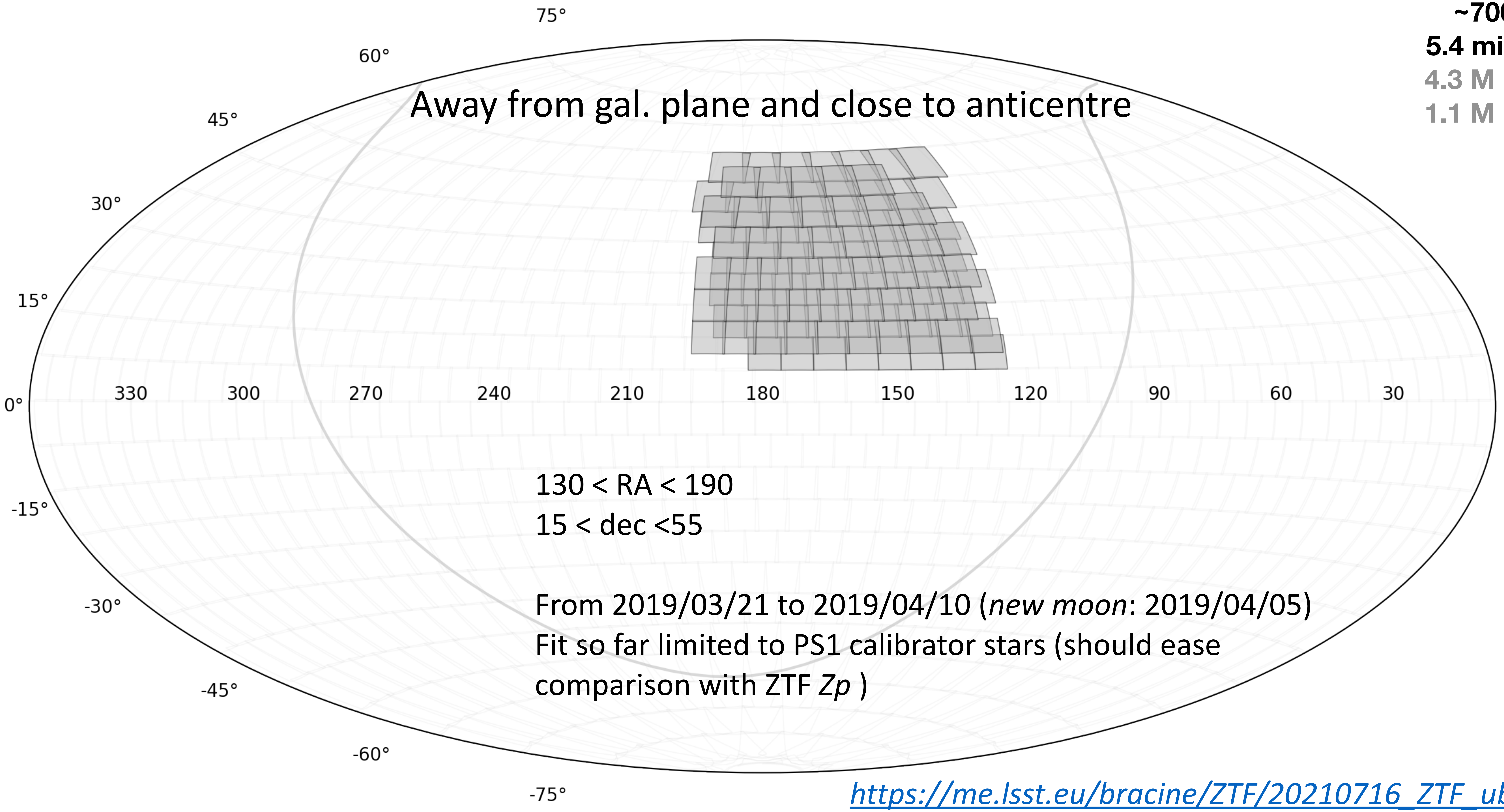
$A^t\,C\,A\,X = A^t\,C\,B$

C : diagonal matrix with weights of $m_{i,j}$ measurements

Covariance of parameters given by: $[A^t\,C\,A]^{-1}$

Test case

~700 000 stars
5.4 million sources
4.3 M in main grid
1.1 M in secondary



Away from gal. plane and close to anticentre

130 < RA < 190
15 < dec <55

From 2019/03/21 to 2019/04/10 (*new moon*: 2019/04/05)
Fit so far limited to PS1 calibrator stars (should ease comparison with ZTF *Zp*)

https://me.lsst.eu/bracine/ZTF/20210716_ZTF_ubercal_first_try/

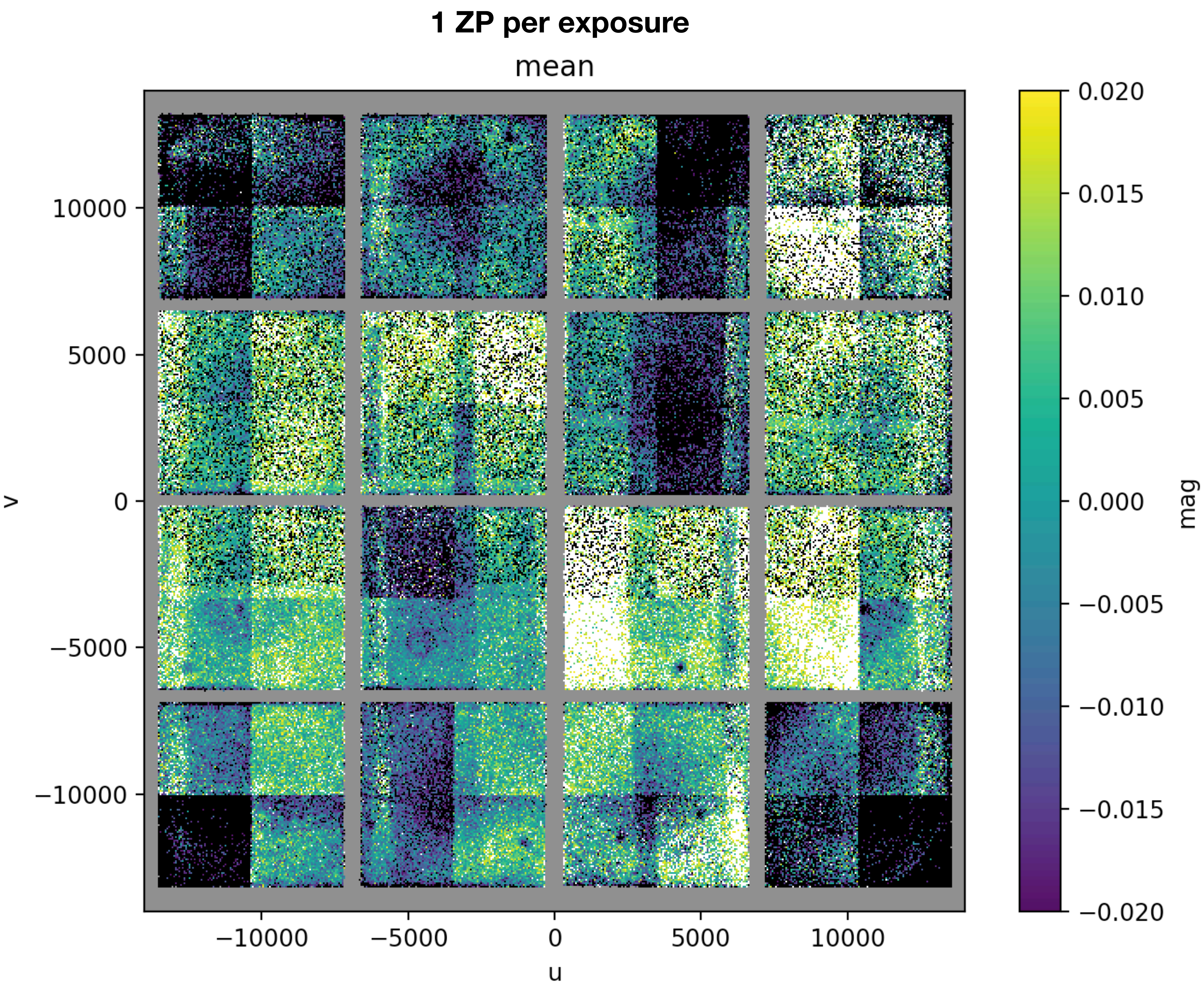
Mean residuals
as a function of focal plane position

$$m^{obs}_j - (m_i + \Delta Z_p + k\, x_{airmass.})$$

We see a clear per-quadrant structure.

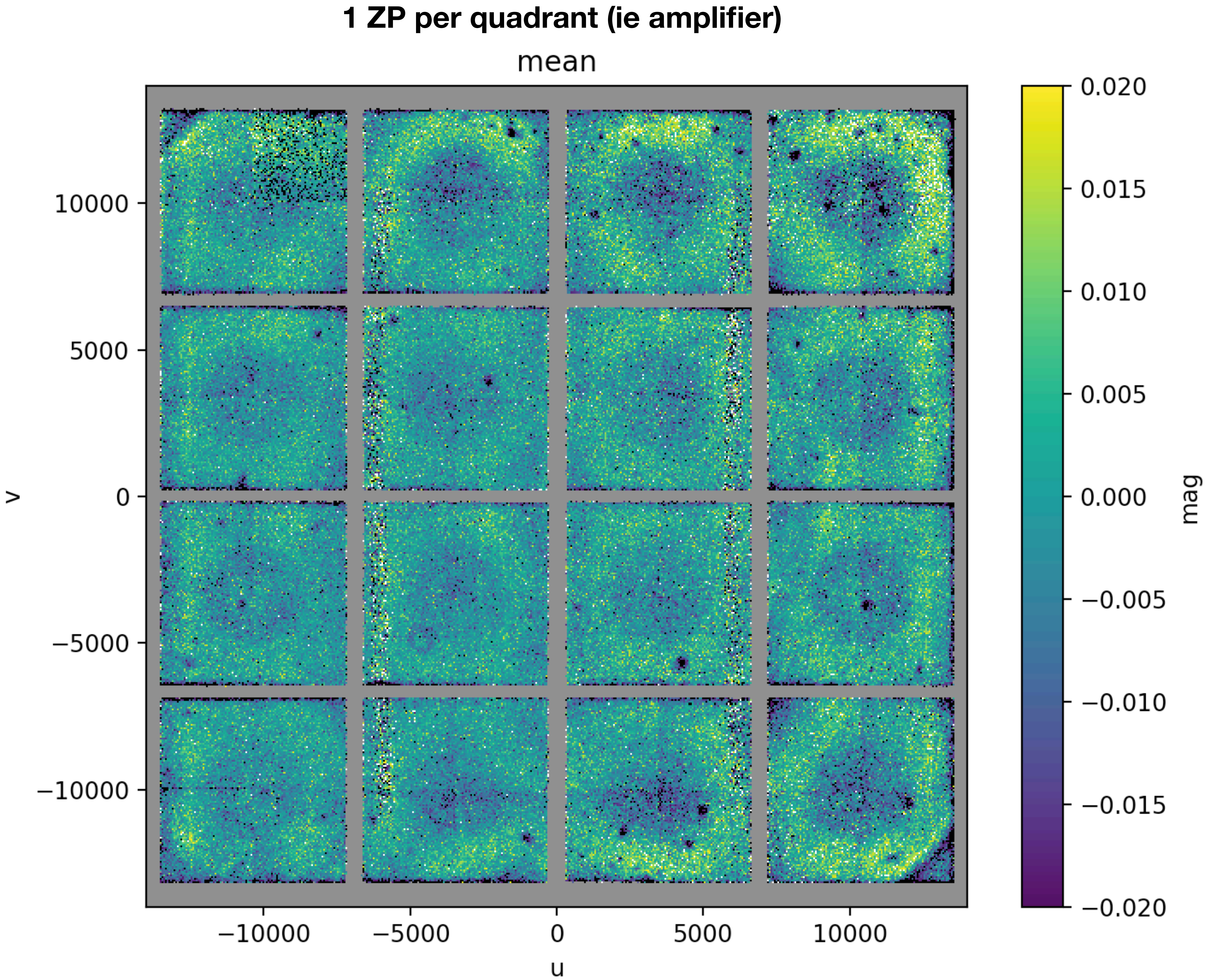
Easier per exposure than per quadrant with the small dithering from ZTF.

We can use starflat ZP correction for the instrumental part, assuming they do not vary much with time



Mean residuals as a function of focal plane position

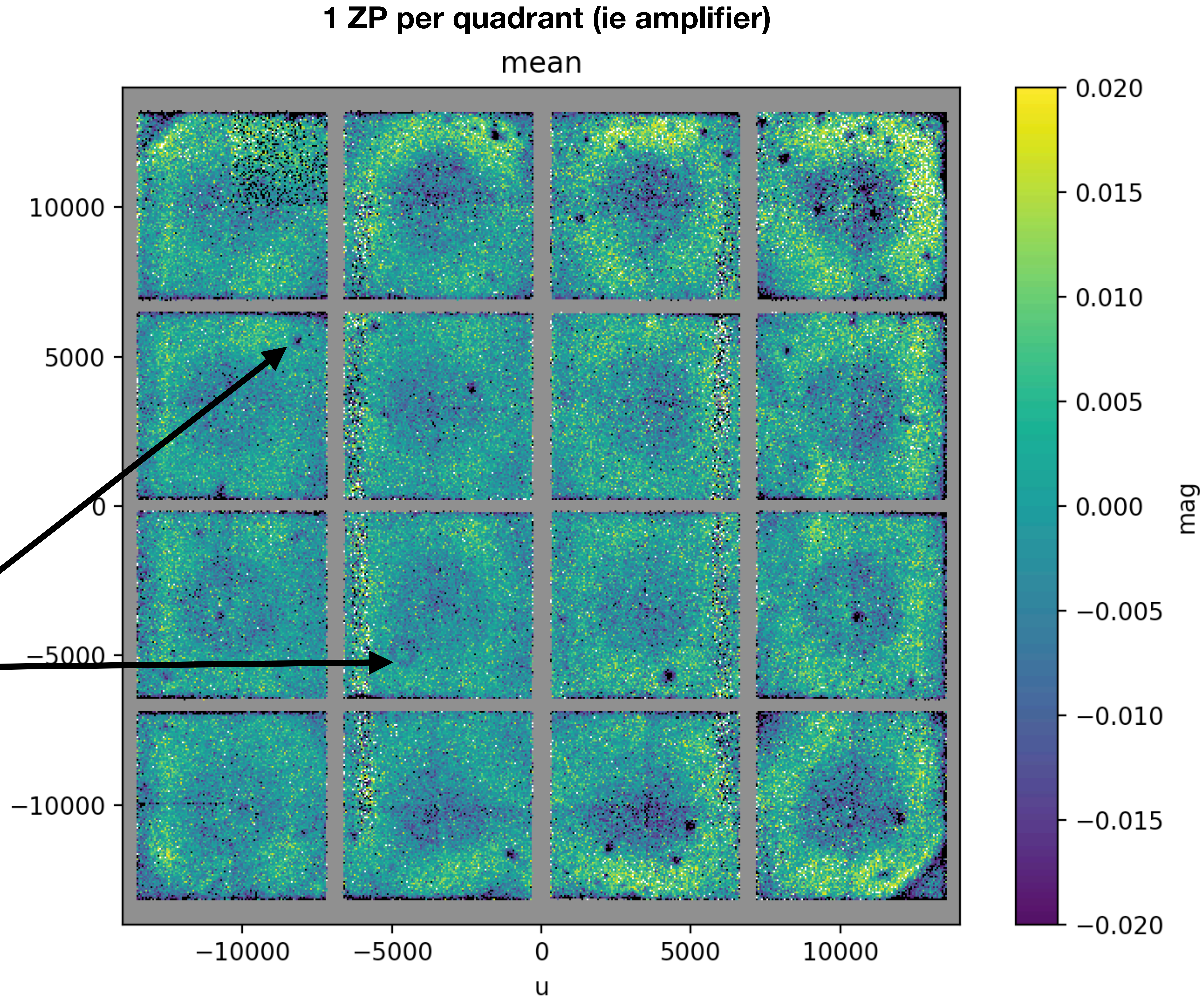
$m^{obs}_j - (m_i + \Delta Z_p + k\, x_{airmass.})$



Mean residuals
as a function of focal plane position

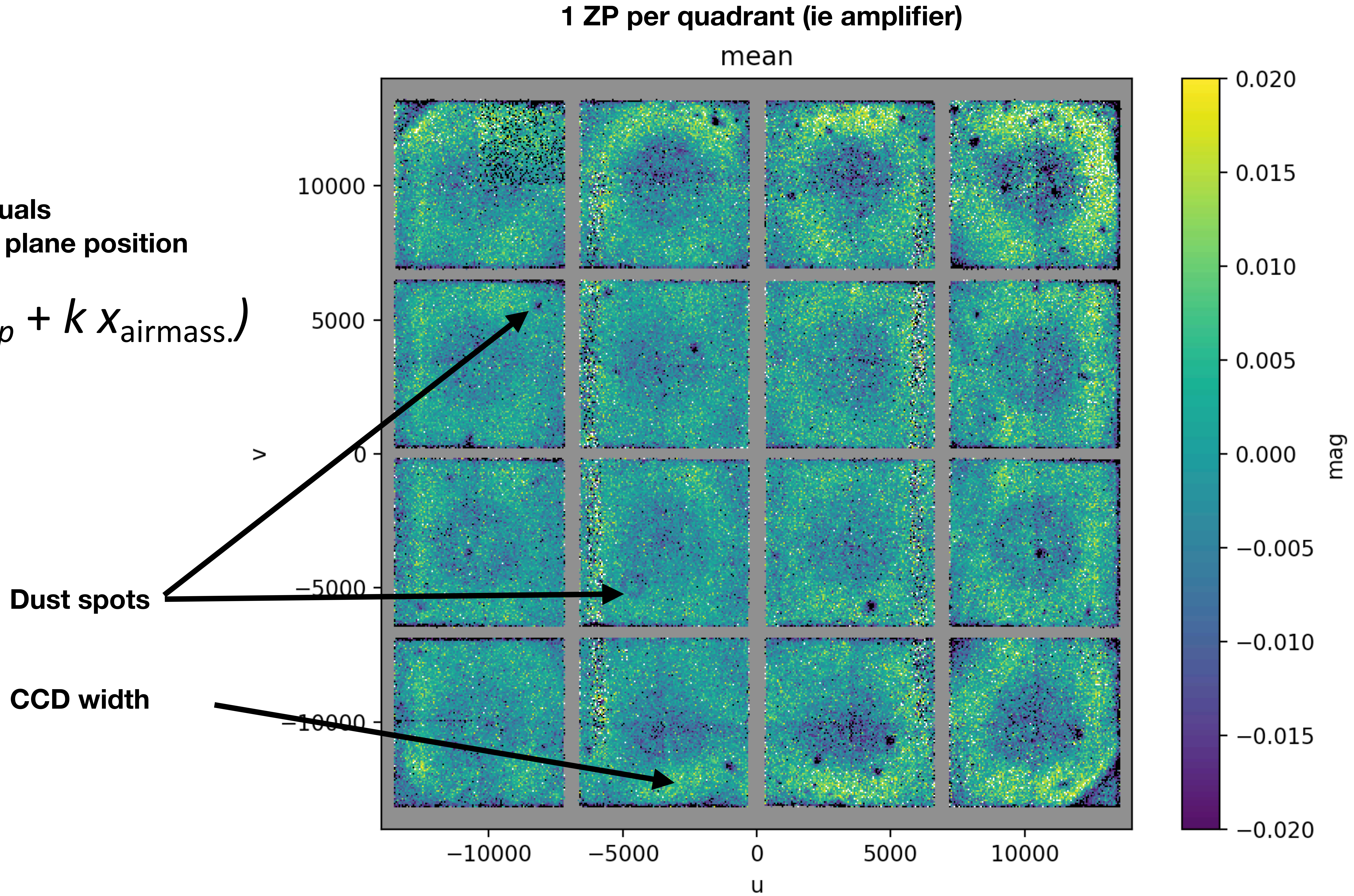
$$m^{obs}_j - (m_i + \Delta Z_p + k\, x_{airmass.})$$

Dust spots



Mean residuals as a function of focal plane position

$$m^{obs}{}_j - (m_i + \Delta Z_p + k\, x_{airmass.})$$



Mean residuals as a function of focal plane position

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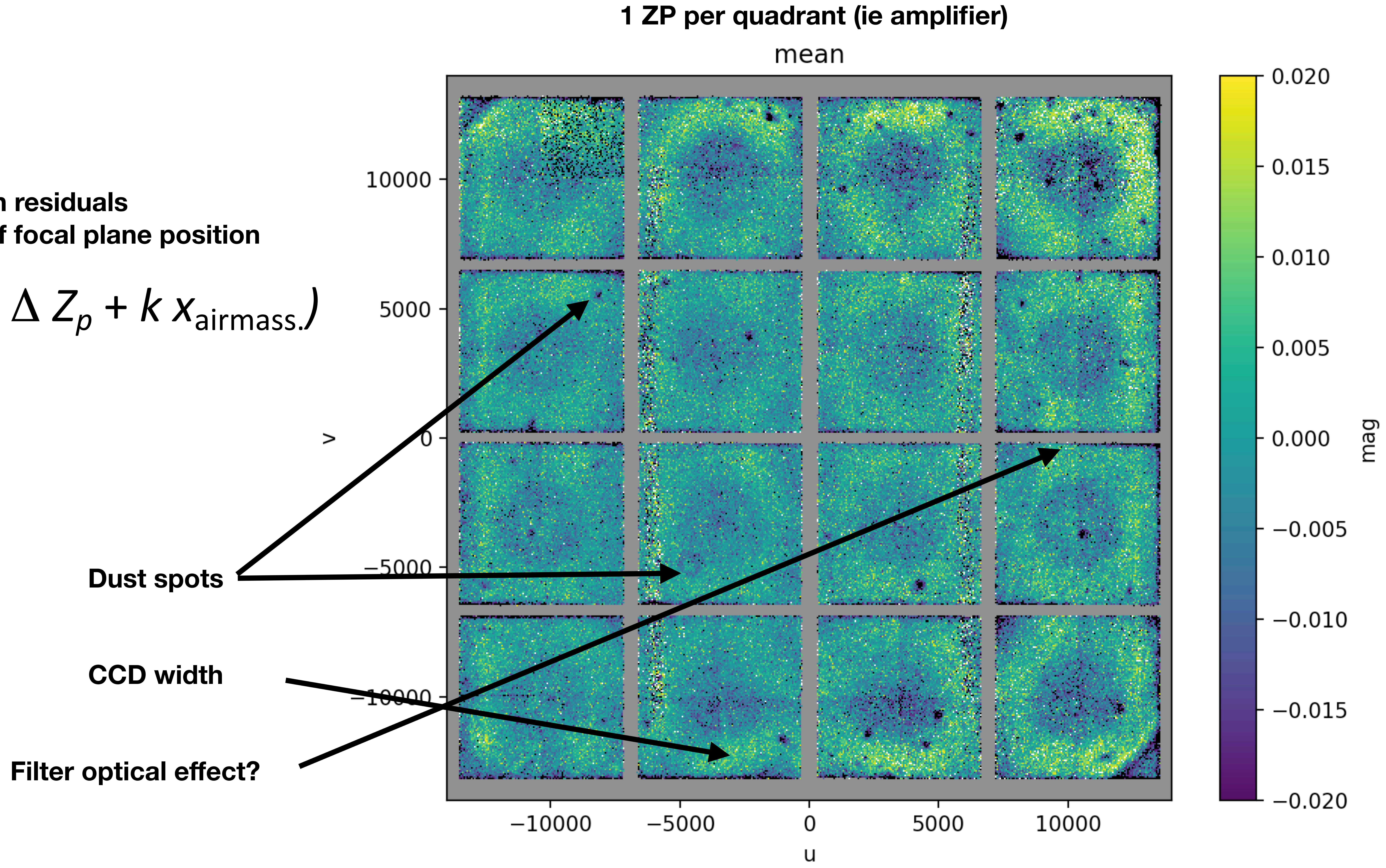
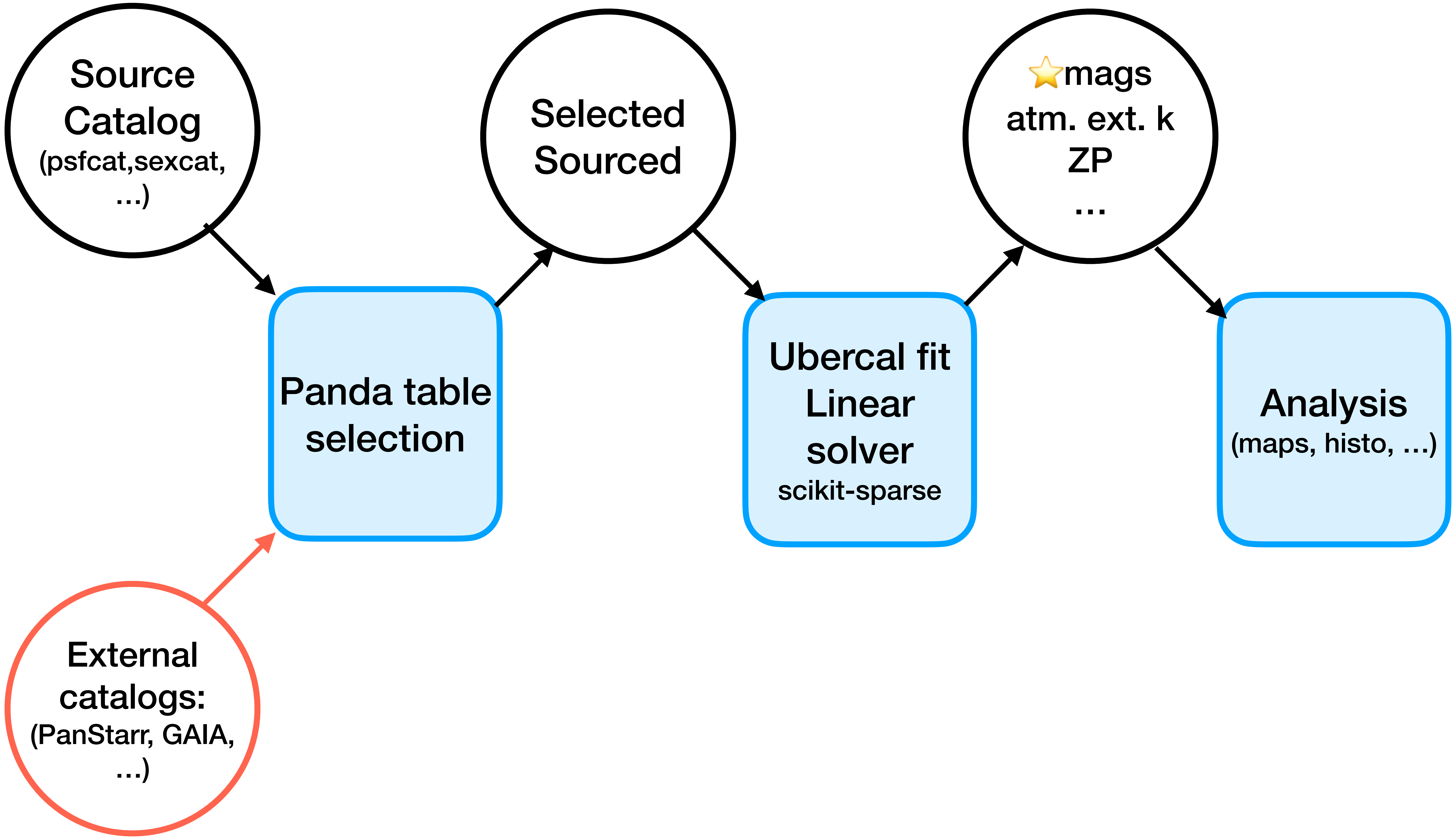
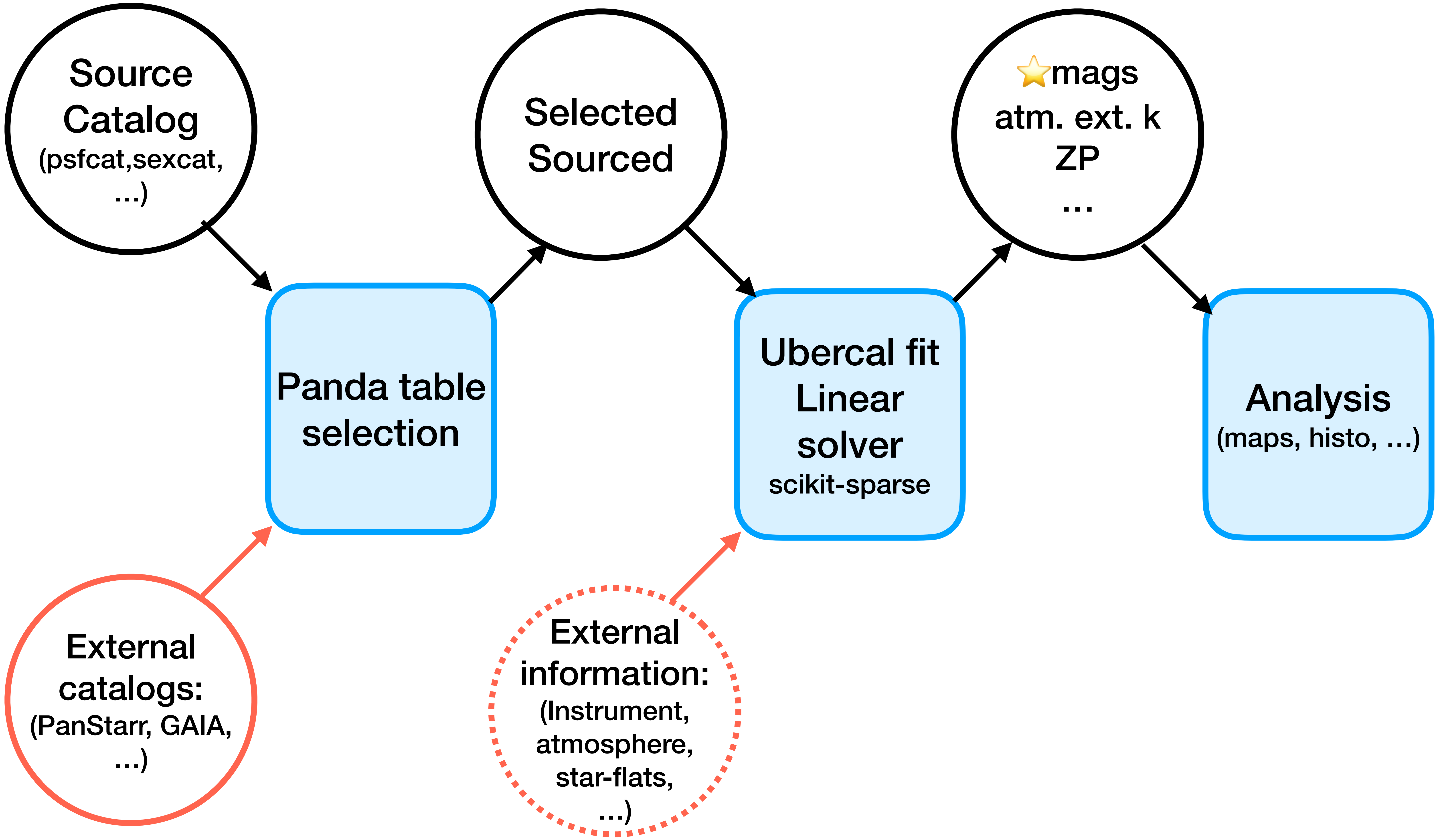



Residuals
Obs mag
1 ZP per exposure
64 ZP per exposure
std (clipped per bin)
std
Standard deviation
Observed mag (roughly offset to PS1 ZP)


Source Catalog
(psfcat,sexcat, ...)
Panda table selection
Selected Sourced
Ubercal fit
Linear solver
scikit-sparse
⭐mags
atm. ext. k
ZP
...
Analysis
(maps, histo, ...)
External catalogs:
(PanStarr, GAIA, ...)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...
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Ubercal fit
Linear solver
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Analysis
(maps, histo, ...)
External catalogs:
(PanStarr, GAIA, ...)
External information:
(Instrument, atmosphere, star-flats, ...)

Summary and outlook (To be finished)

Looks promising, main parts of **pipeline** available on ***GitHub***

Current developments:

-Errors estimates:

diagonal of (non sparse) inverse Hessian ***[A^t C A] : using selinv (from saunerie module, 🙏 LPNHE)***
Will try extracting the main error modes.

-Test method on more data

-6 month of r filter data running.

-Use aperture photometry with starflat correction to close the loop.

-Cross check with Gaia photometry

-Study color effects etc.

What about LSST?

-crosschecks with forward calibration results on /DES ?

-Ubercal can be used on commissioning data (dithering bonus !)

- Possible future tests on refined LSST simulations to understand error propagation effects on calibration wrt cadence, dithering, clouds, dust, color effects, …