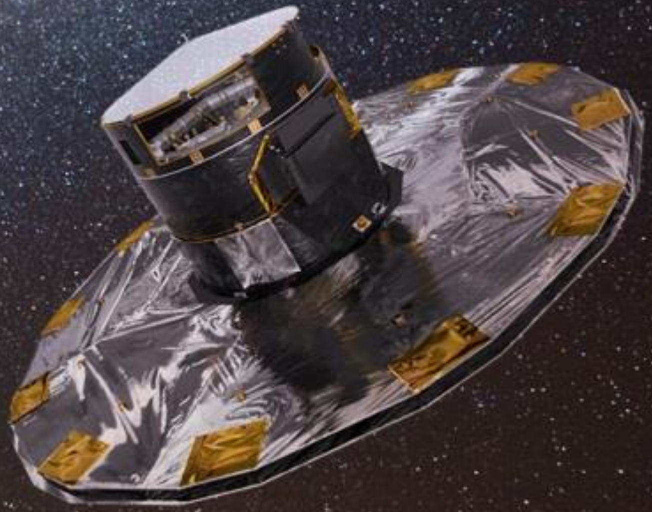
Gaia, an all-sky astrometric and photometric survey

Josep Manel Carrasco
on behalf of Gaia-photometry group
University of Barcelona, ICCUB-IEEC



Precision Astronomy with fully depleted CCDs, 1-2 Dec 2016

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Focal plane

106 CCDs , 938 million pixels, 2800 cm^2
pixel size= 59 mas, angular resolution=0.12"

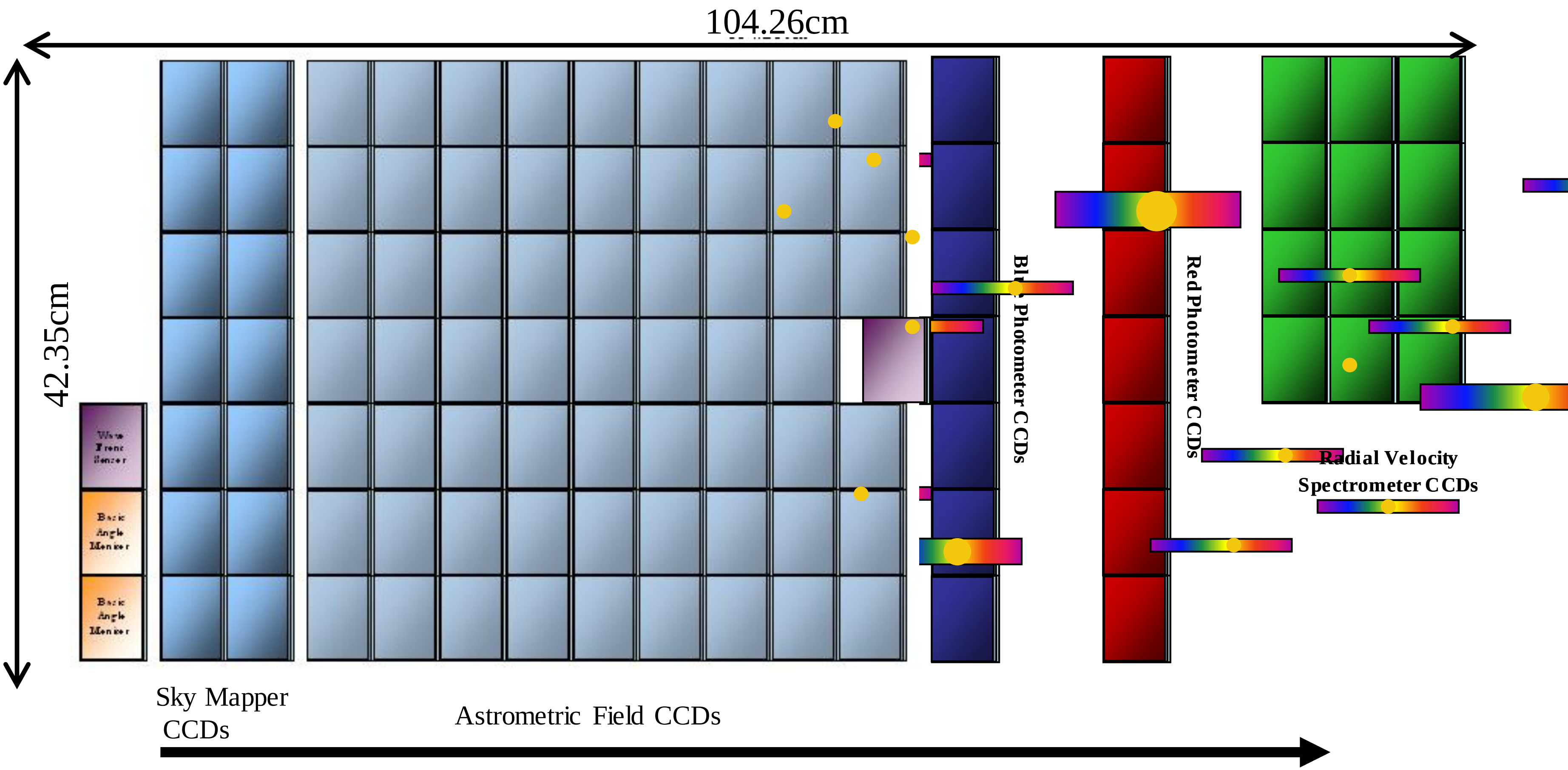
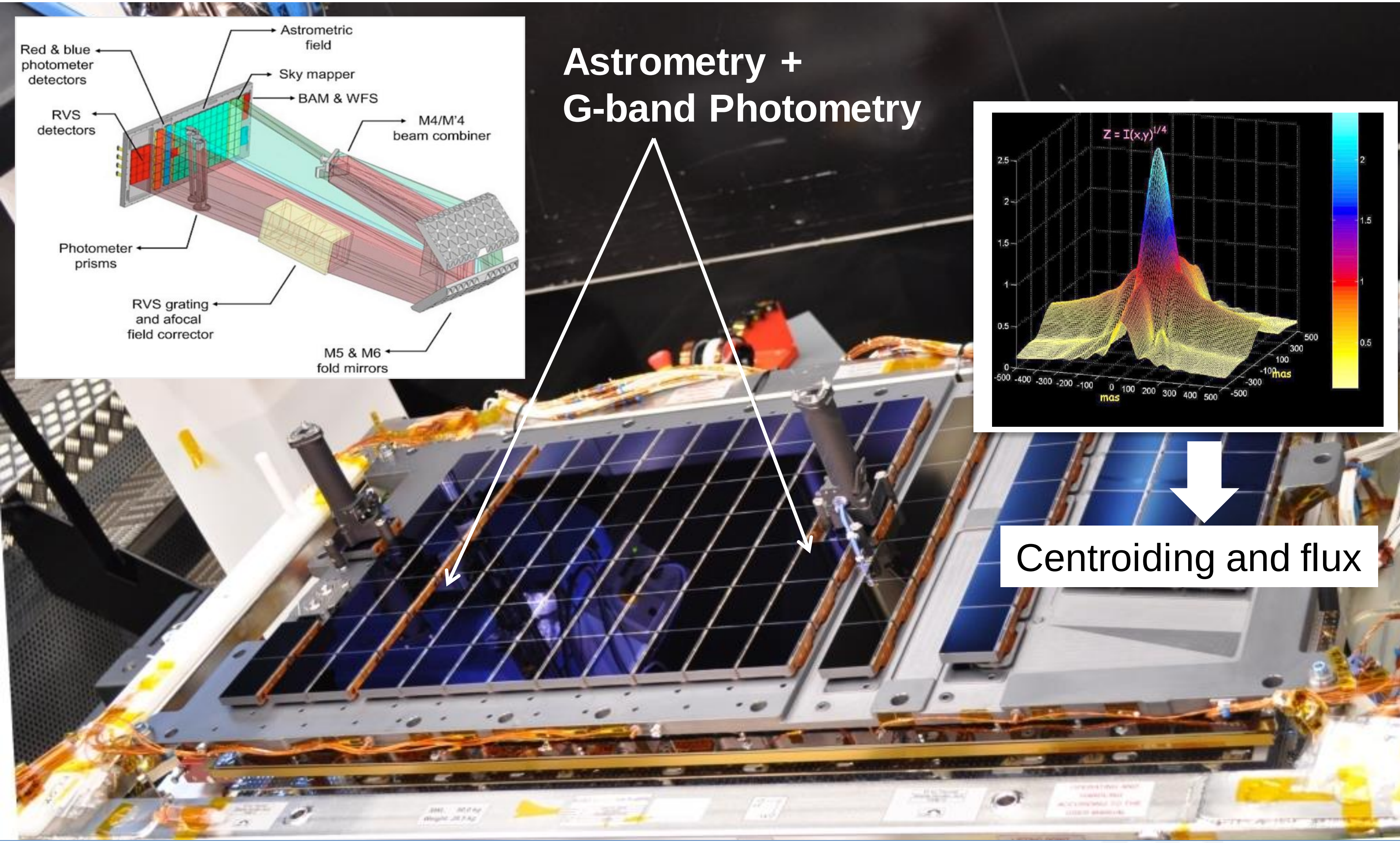


Image motion: Delayed integration

Figure courtesy Alex Short

Photometric instruments



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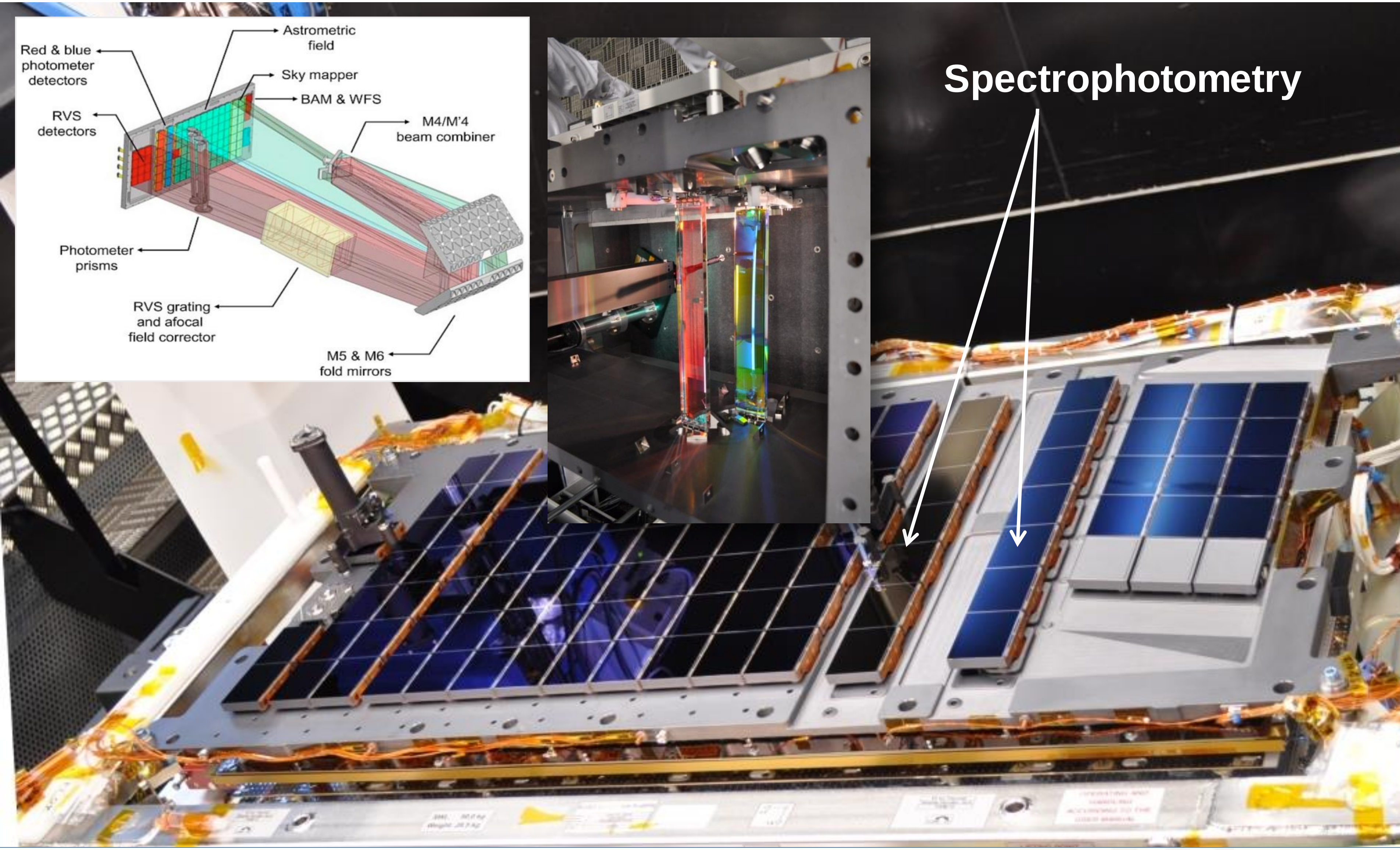
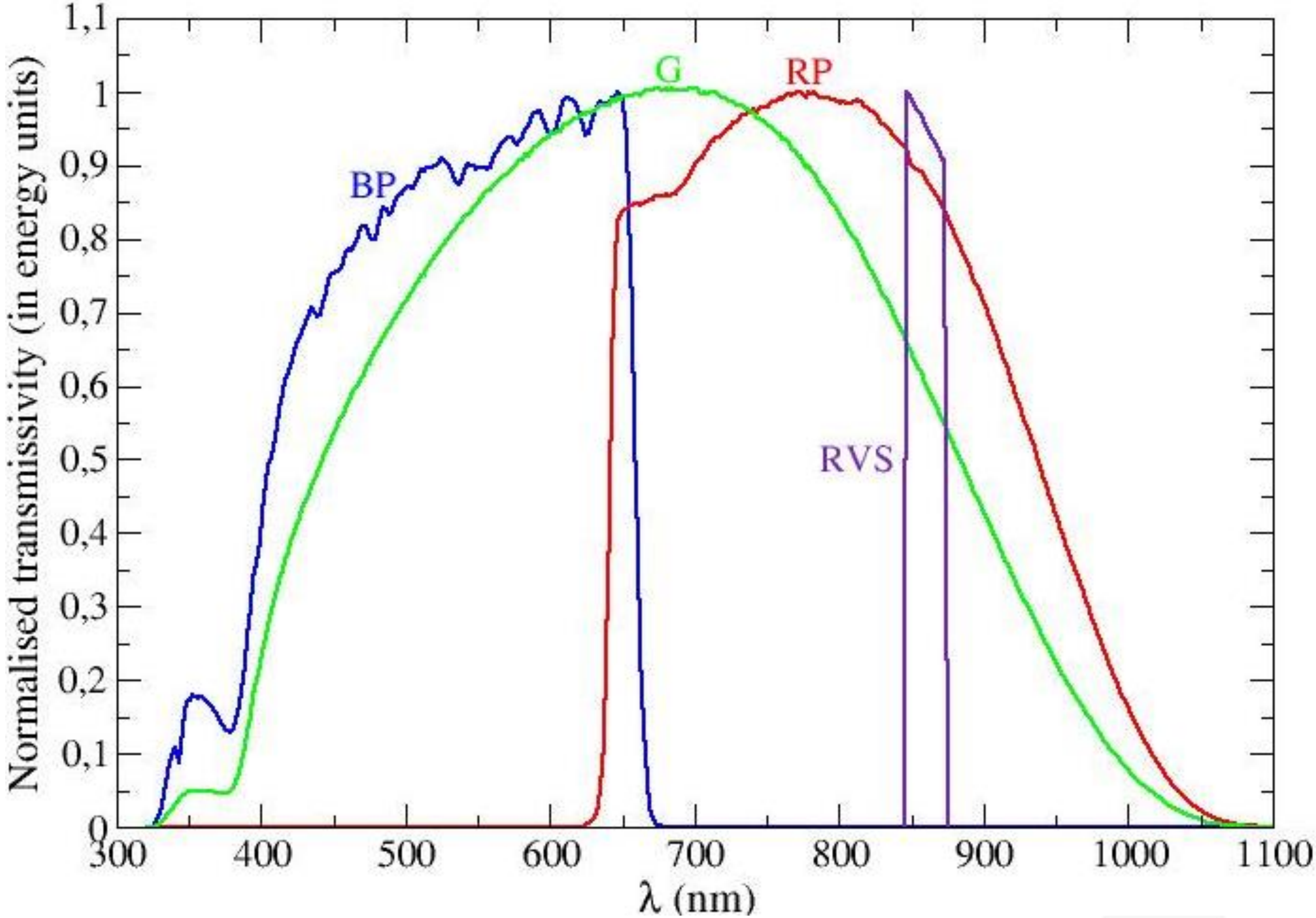
Photometric instruments



Photometric passbands



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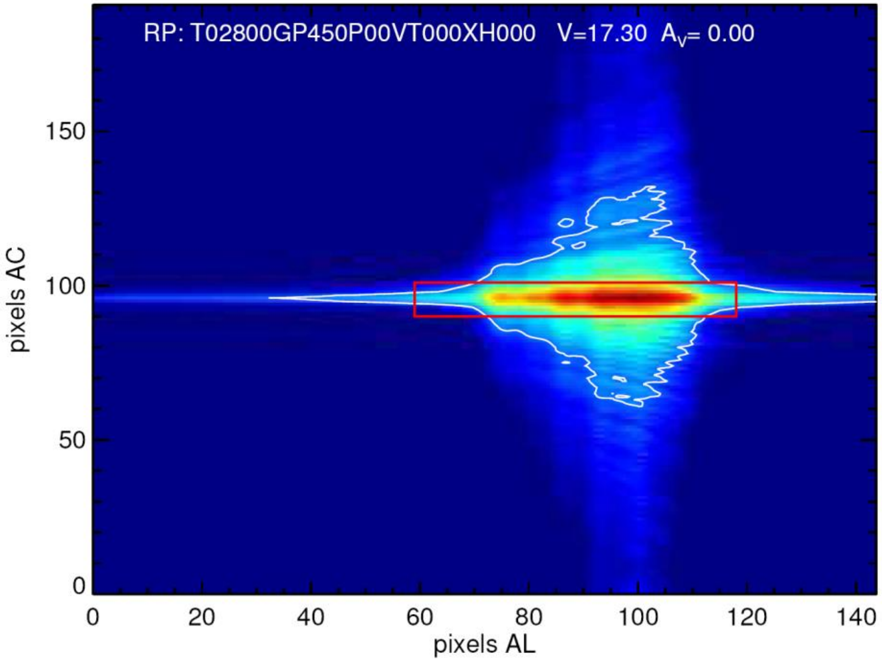
Spectrophotometry: instrument

Blue photometer:	330–680 nm	3-27 nm/pixel
Red photometer:	640–1050 nm	7-15 nm/pixel



Red spectra of a M-dwarf (V=17.3)

Red box: extracted window sent to the Earth

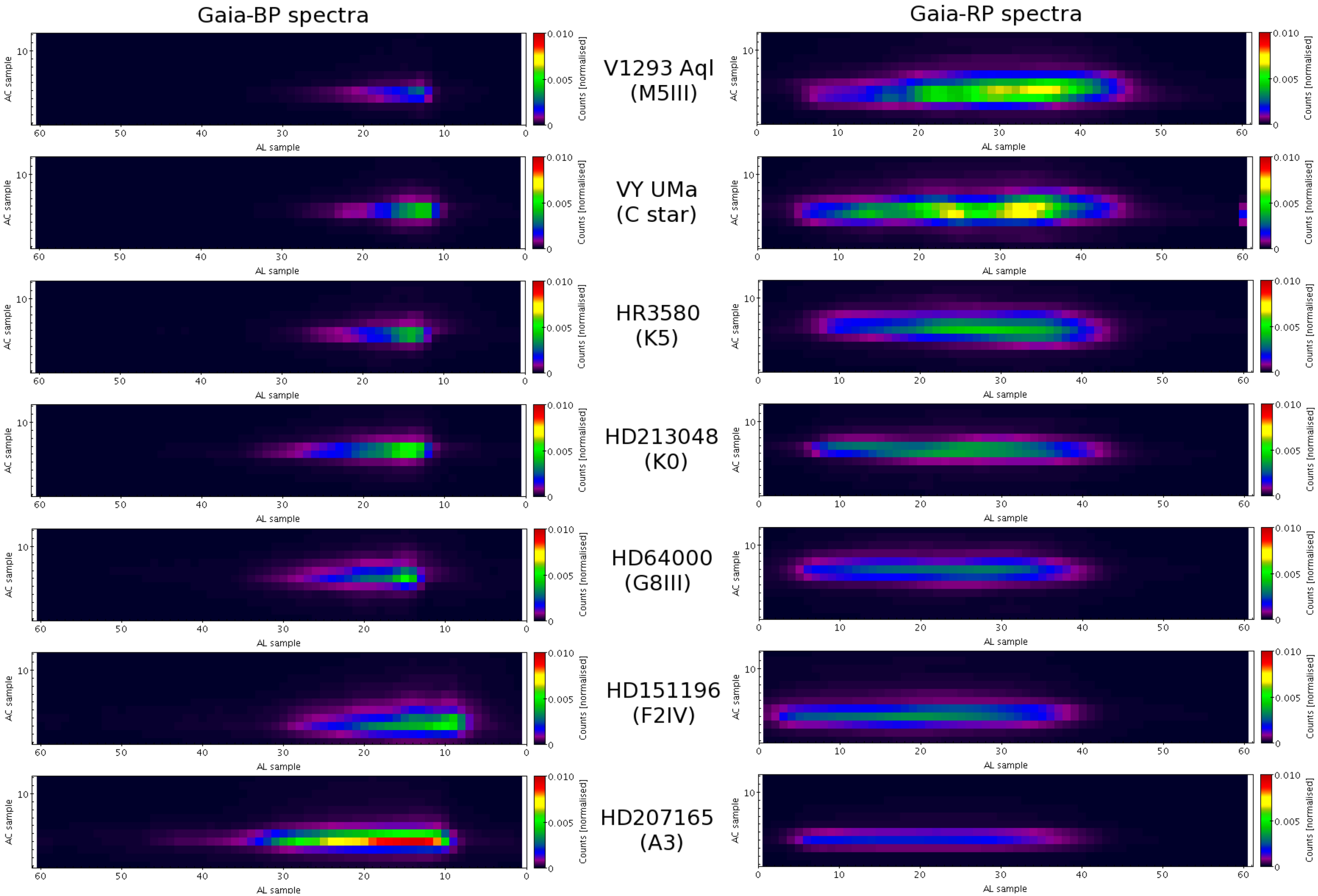
Window size: 60x12 = 3.54” x 2.12”

2D and 1D windows

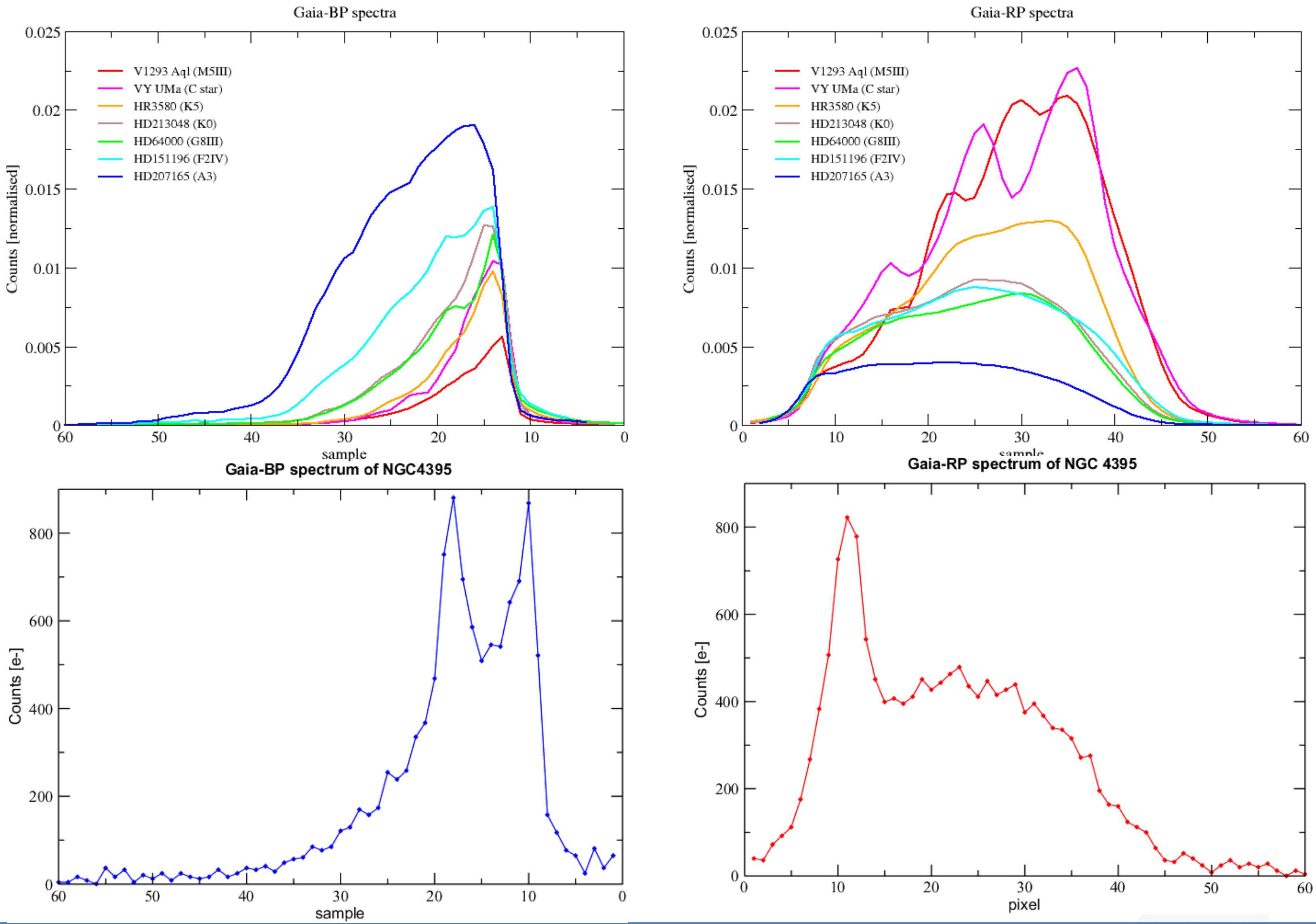
Figures courtesy of DPAC

Figure courtesy Anthony Brown

Spectrophotometry: examples



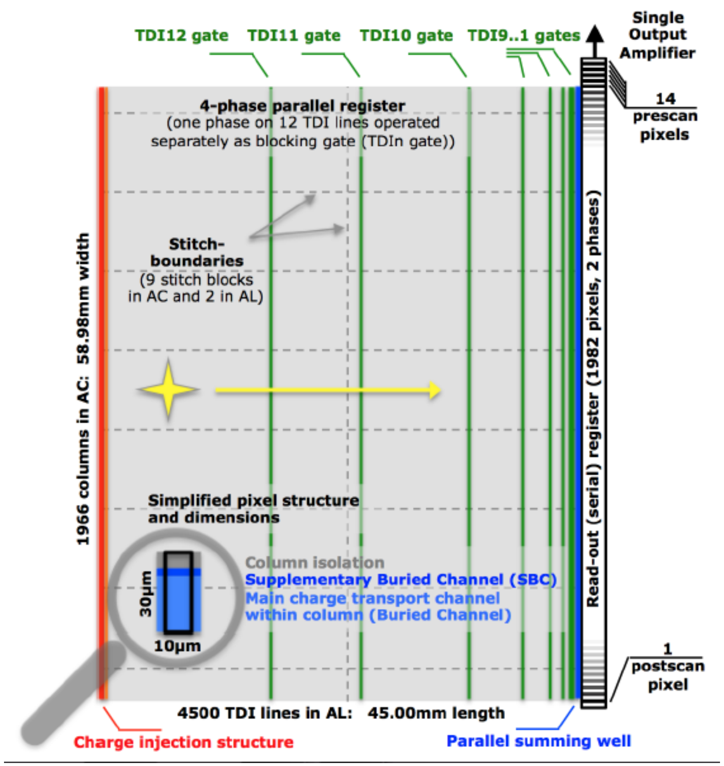
Spectrophotometry: examples

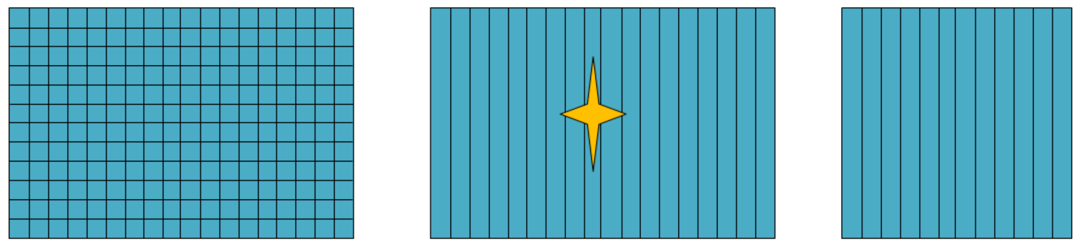


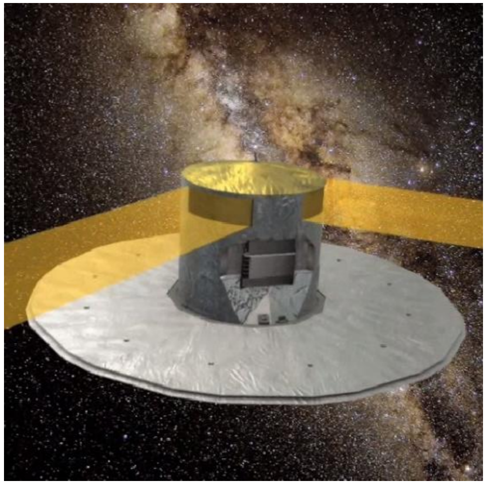
Instrumental effects and calibration

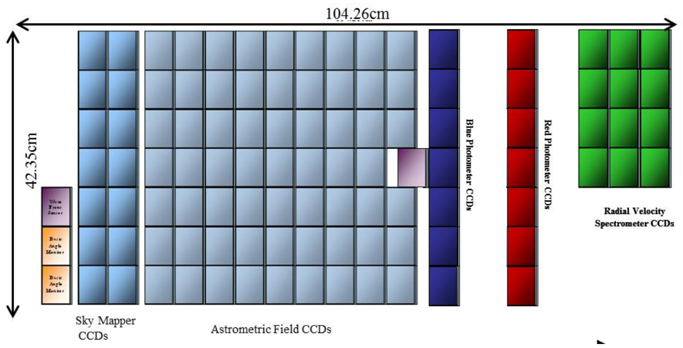
UNITS OF CALIBRATION = "instrument"

FoV	Gate	Window class	AC position	Time









Instrumental effects and calibration

UNITS OF CALIBRATION = "instrument"

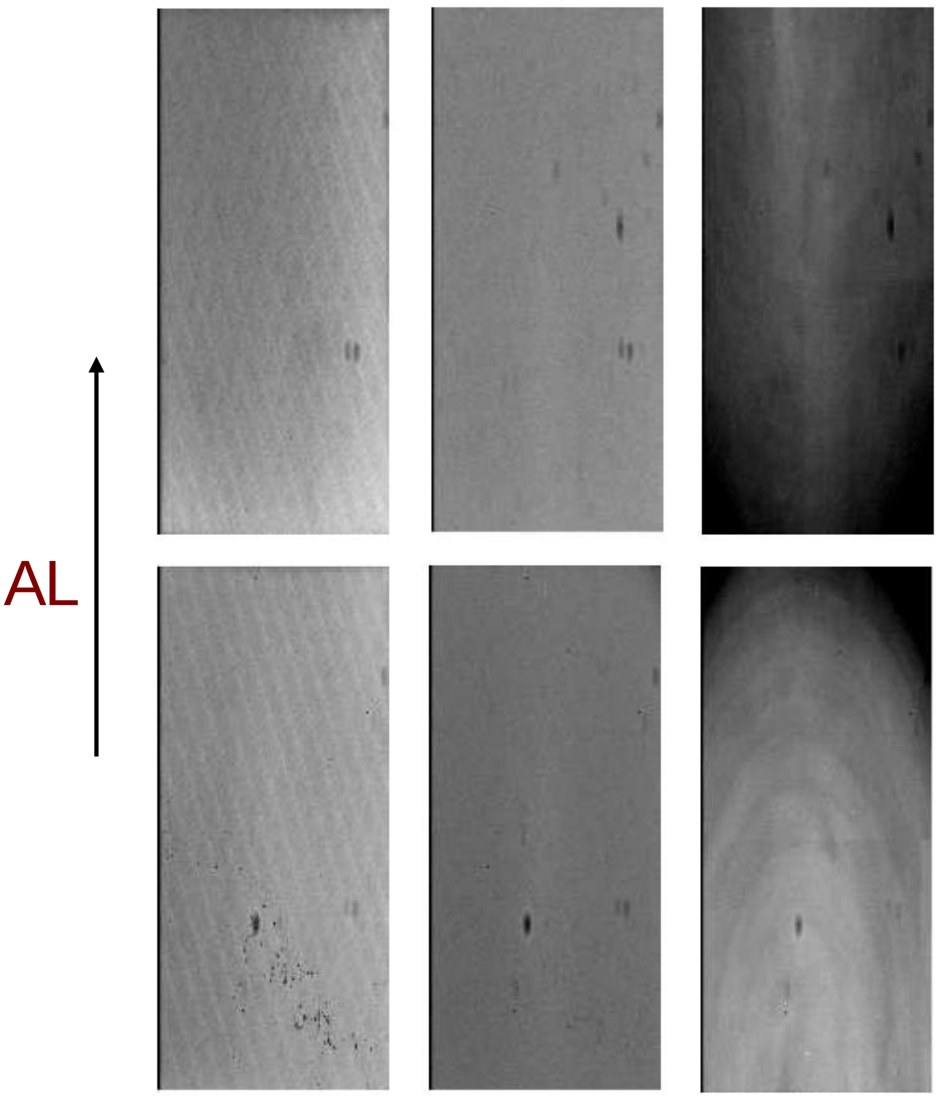
- FoV
- Gate
- Window class
- AC position
- Time

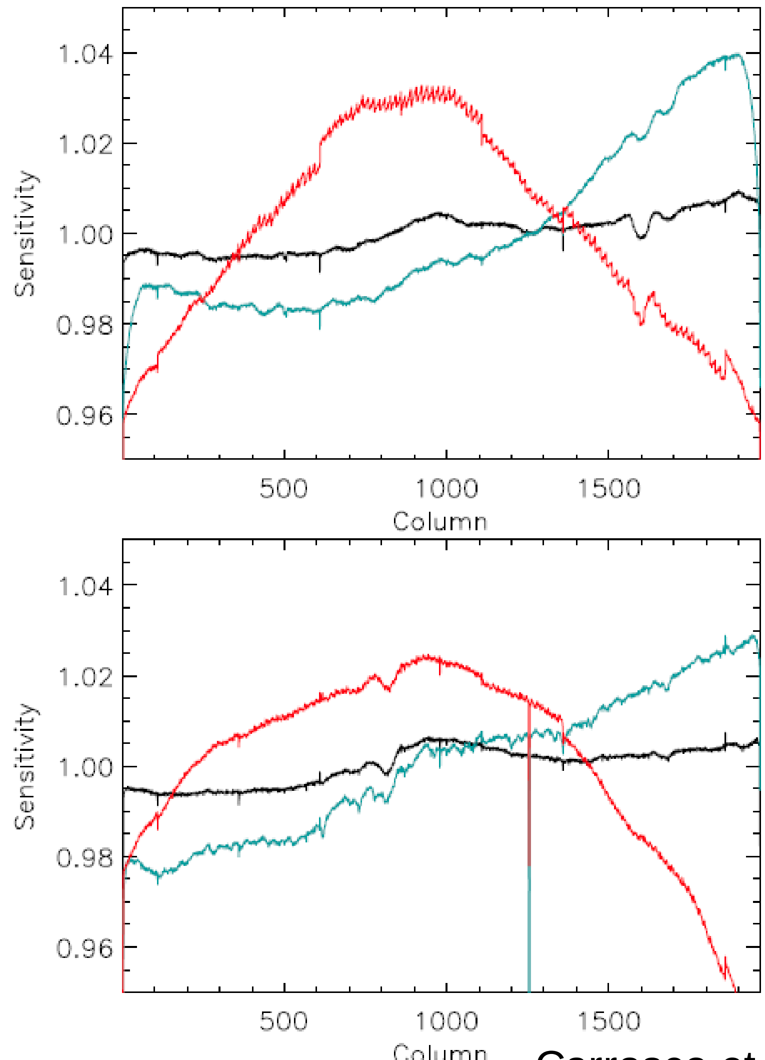
INSTRUMENTAL EFFECTS

- Sensitivity (optics+CCDs)

Examples

CCD flatfields





Carrasco et al (2016)

Instrumental effects and calibration

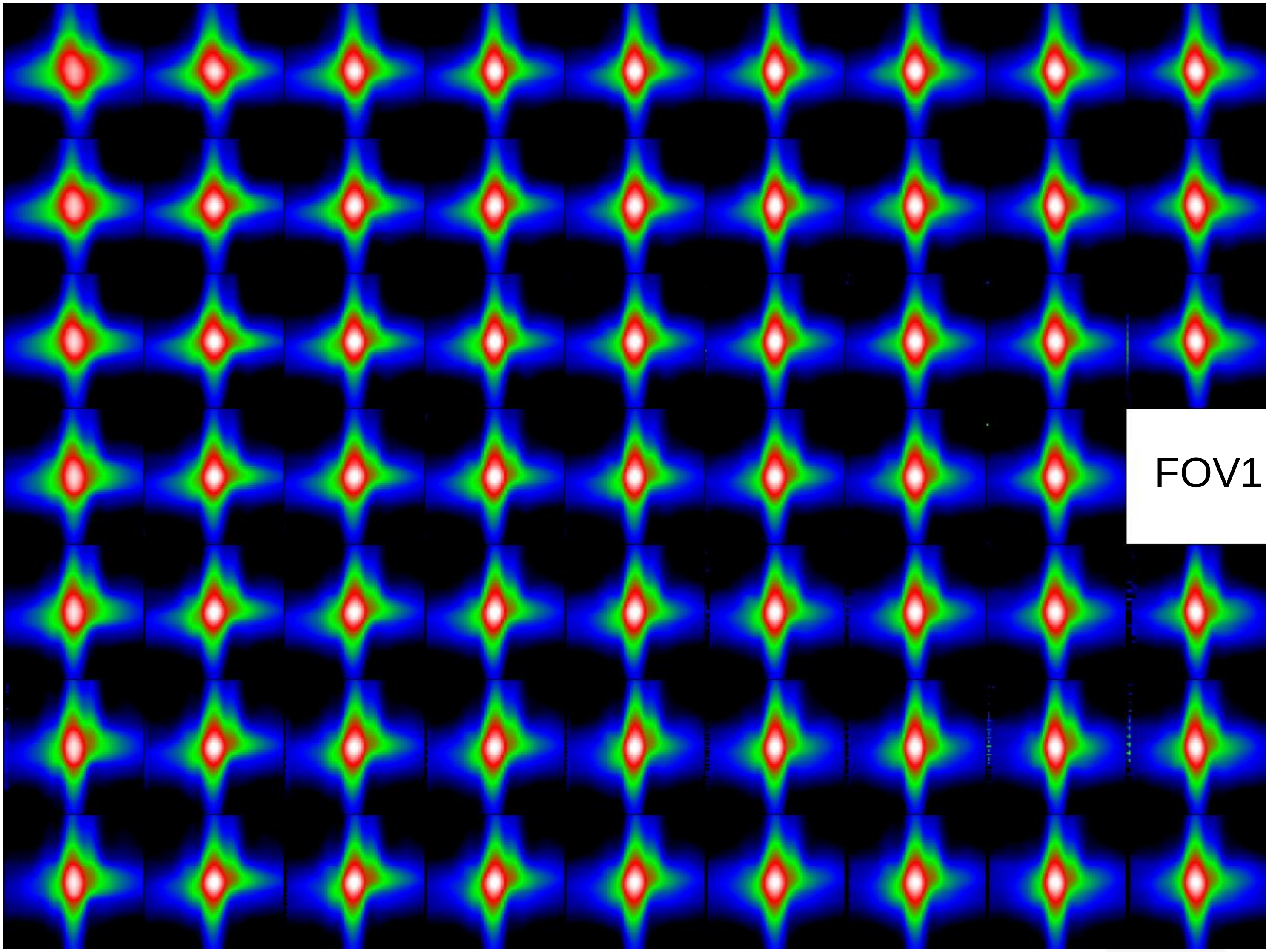
UNITS OF CALIBRATION = "instrument"

- FoV
- Gate
- Window class
- AC position
- Time

INSTRUMENTAL EFFECTS

- Sensitivity (optics+CCDs)
- PSF/LSF (saturation)

PSF map



Instrumental effects and calibration

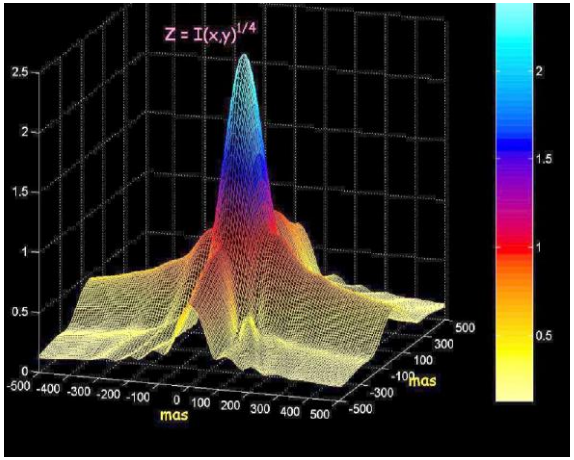
UNITS OF CALIBRATION = "instrument"

- FoV
- Gate
- Window class
- AC position
- Time

INSTRUMENTAL EFFECTS

- Sensitivity (optics+CCDs)
- Aperture
- PSF/LSF (saturation)

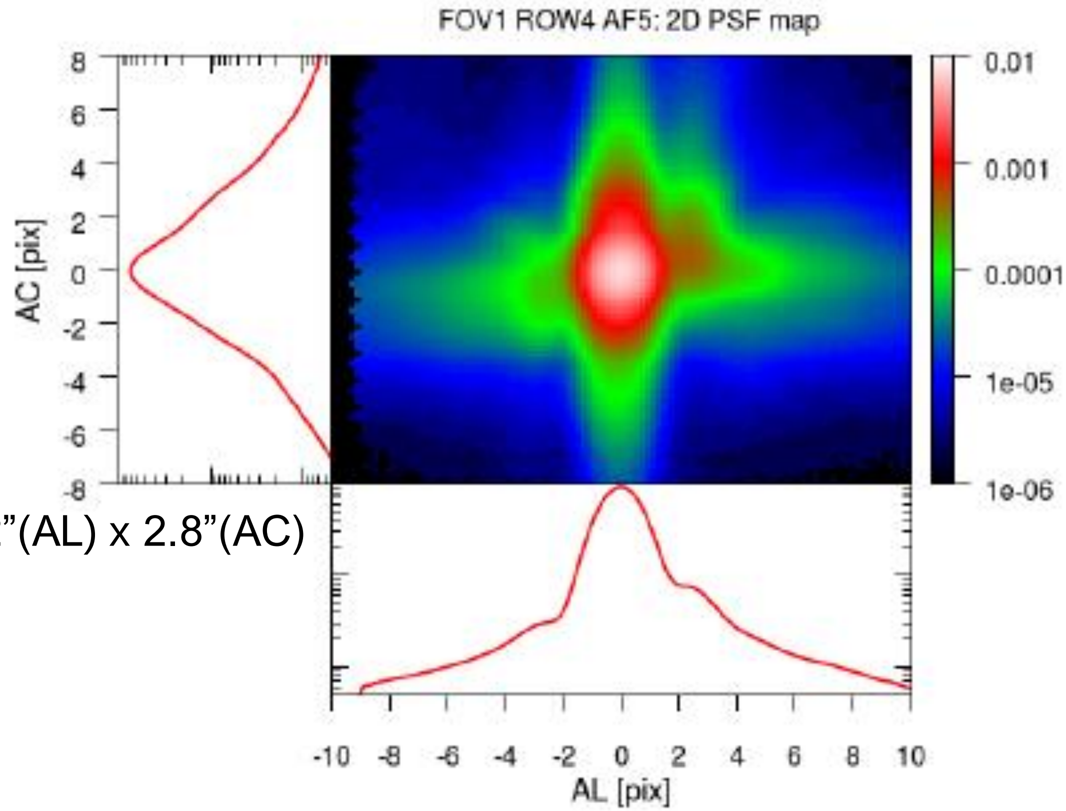
Aperture correction



Window Class	Type	AF	BP/RP
WC0	2D	$G \leq 13$	$G \leq 11.5$
WC1	Long 1D	$13 < G \leq 16$	$11.5 < G \leq 16$
WC2	Short 1D	$G > 16$	$G > 16$

→ PSF fitting

LSF fitting



Median AL FWHM = 103 mas

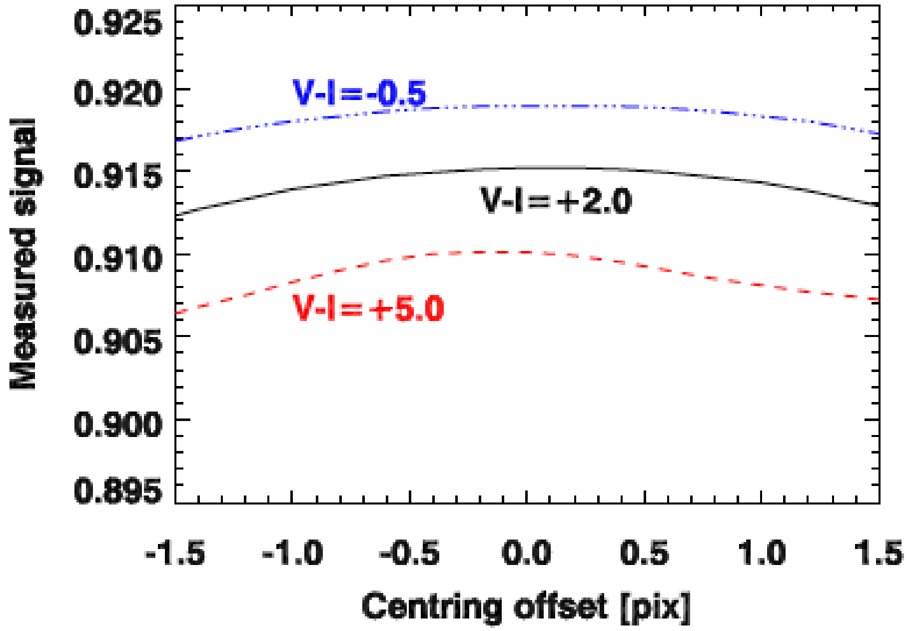
1.2”(AL) x 2.8”(AC)

Fabricius et al (2016)

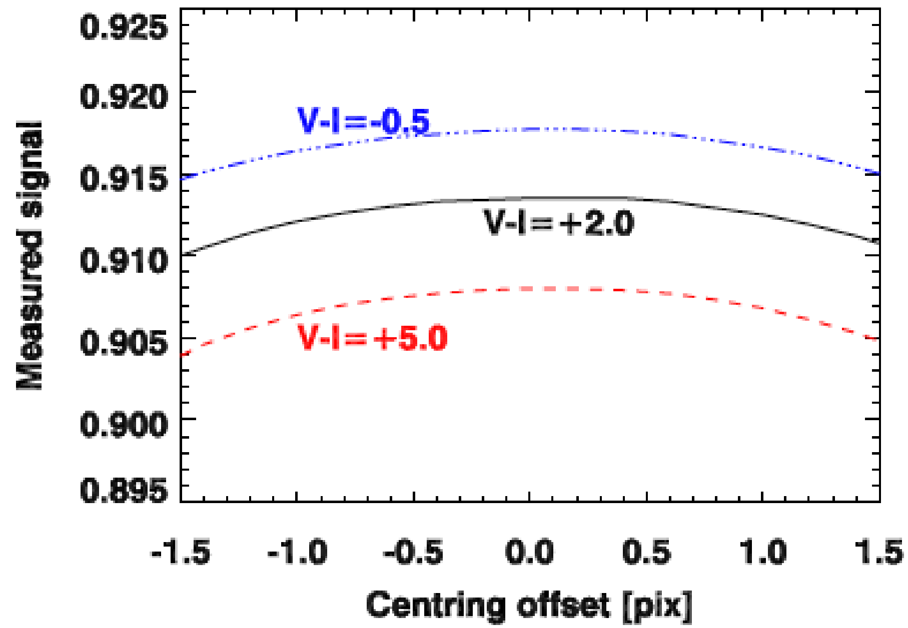
Aperture correction

1-2% variation

AF S9R1T2



No AC motion



Maximum AC motion

Calibration as function of colour, centring offset and AC motion

Carrasco et al (2016)

Instrumental effects and calibration

UNITS OF CALIBRATION = “instrument”

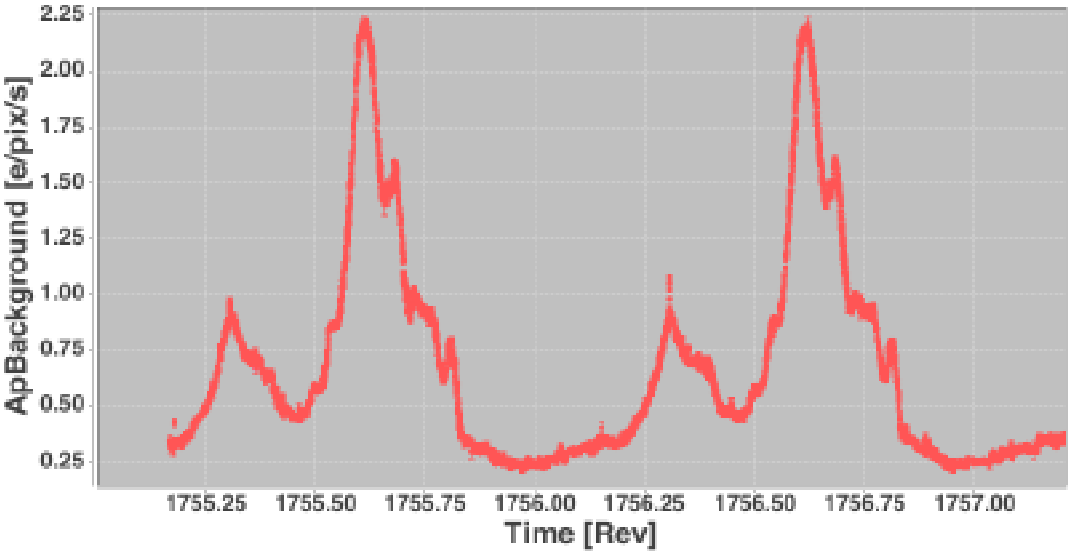
- FoV
- Gate
- Window class
- AC position
- Time

INSTRUMENTAL EFFECTS

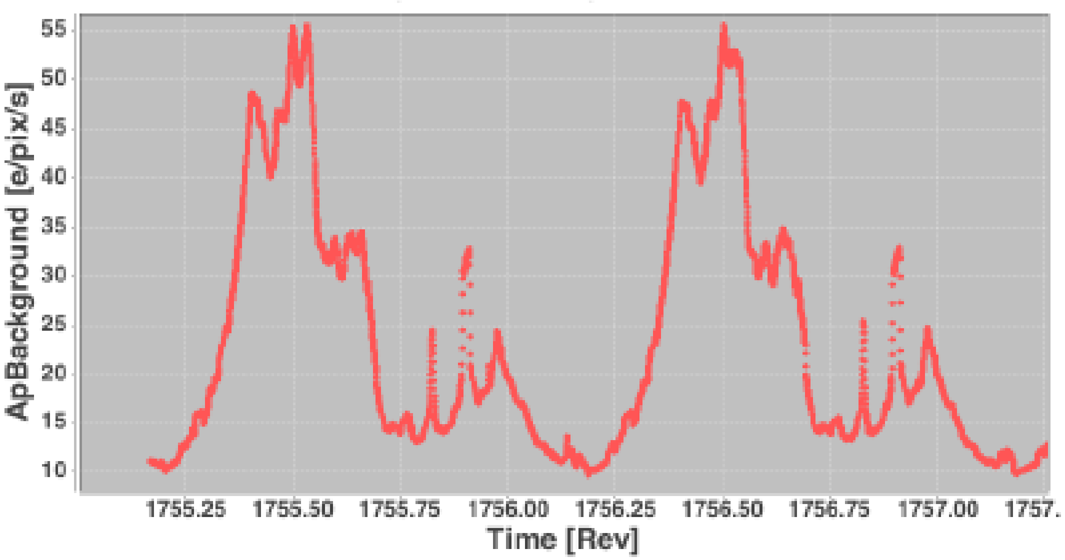
- Sensitivity (optics+CCDs)
- Aperture
- Background & straylight
- PSF/LSF (saturation)

Background

Variation due to straylight



BP row 1



AF row 7

Fabricius et al (2016)

Instrumental effects and calibration

UNITS OF CALIBRATION = "instrument"

- FoV
- Gate
- Window class
- AC position
- Time

INSTRUMENTAL EFFECTS

- Sensitivity (optics+CCDs)
- Aperture
- Background & straylight
- Gain, bias, CTI
- PSF/LSF (saturation)

CTI effect on BP/RP spectra

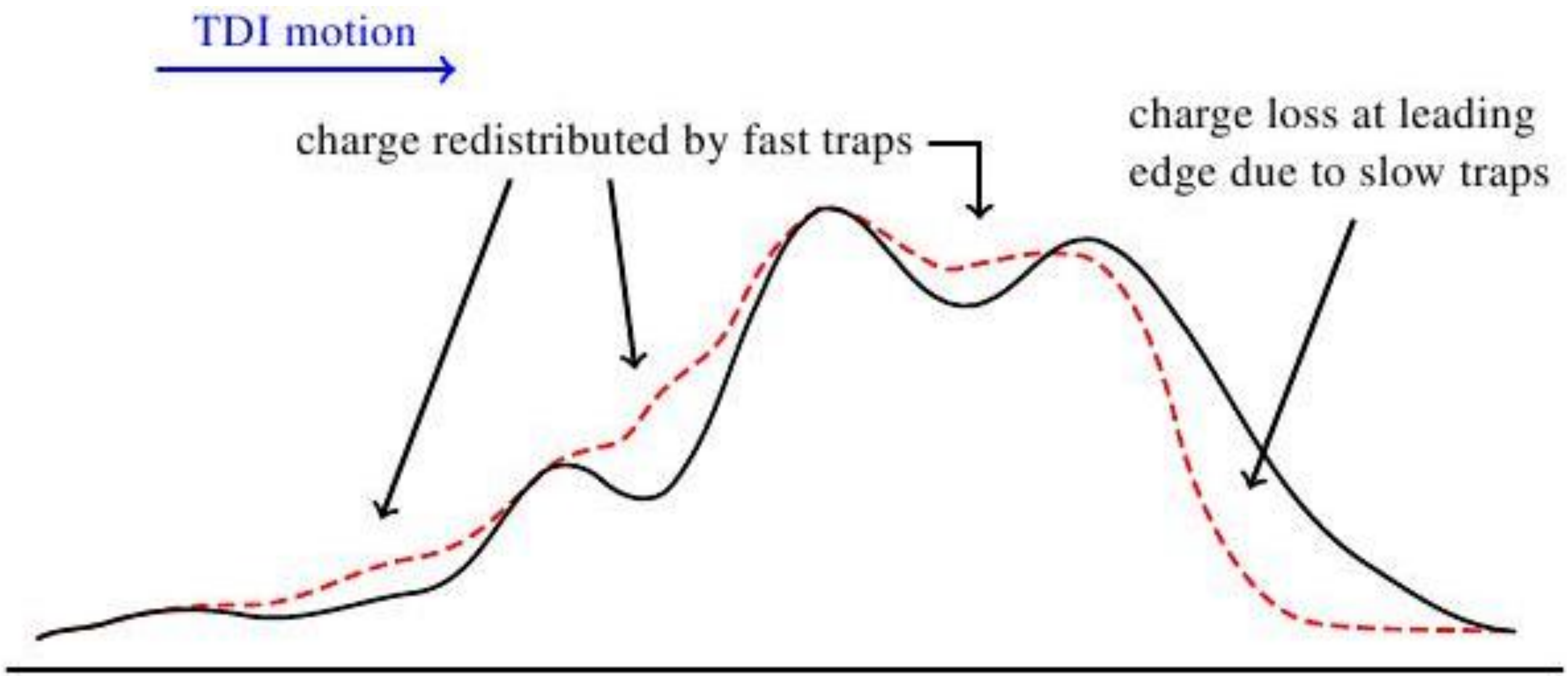


Figure courtesy Anthony Brown

CTI distorts the shape of the spectra → Worse redshifts

2 methods to face the problem: Reconstruction vs Prediction

Instrumental effects and calibration

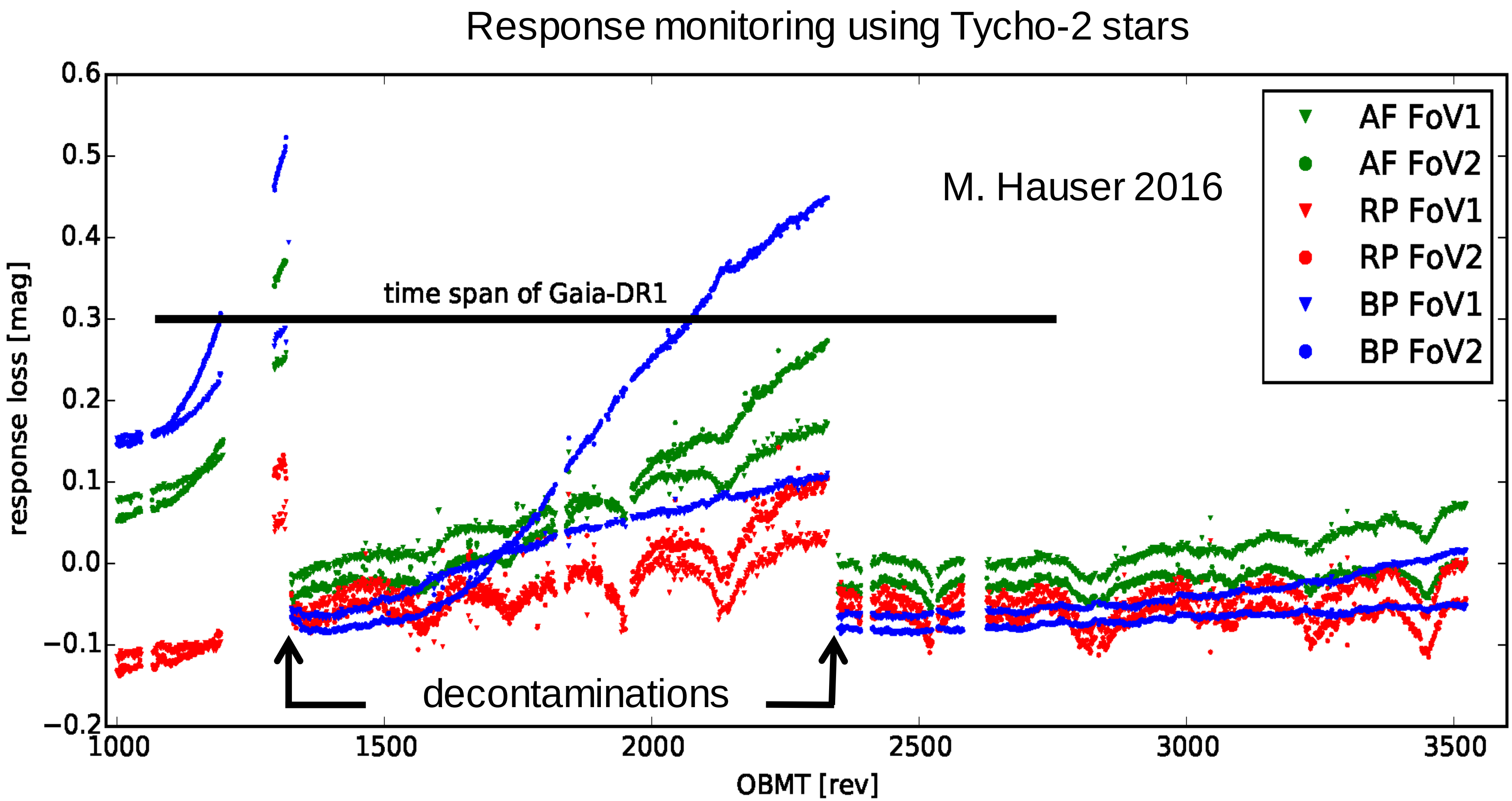
UNITS OF CALIBRATION = “instrument”

- FoV
- Gate
- Window class
- AC position
- Time

INSTRUMENTAL EFFECTS

- Sensitivity (optics+CCDs)
- Aperture
- Background & straylight
- Gain, bias, CTI
- PSF/LSF (saturation)
- Contamination

Contamination



Instrumental effects and calibration

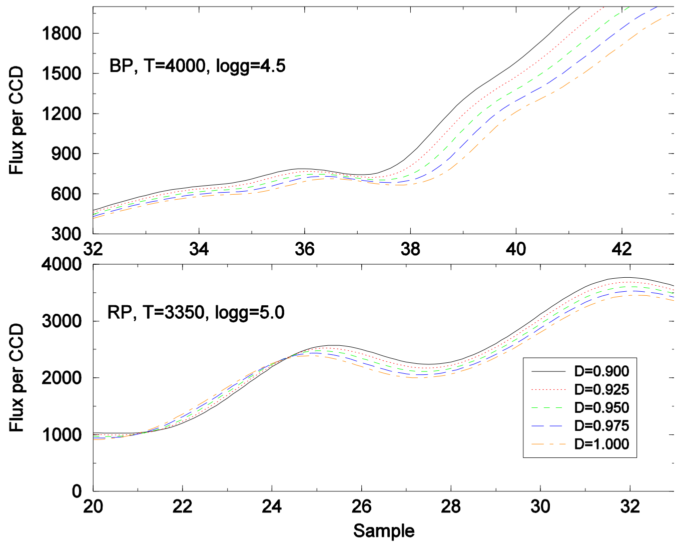
UNITS OF CALIBRATION = "instrument"

- FoV
- Gate
- Window class
- AC position
- Time

INSTRUMENTAL EFFECTS

- Sensitivity (optics+CCDs)
- Aperture
- Background & straylight
- Gain, bias, CTI
- PSF/LSF (saturation)
- Contamination
- Dispersion

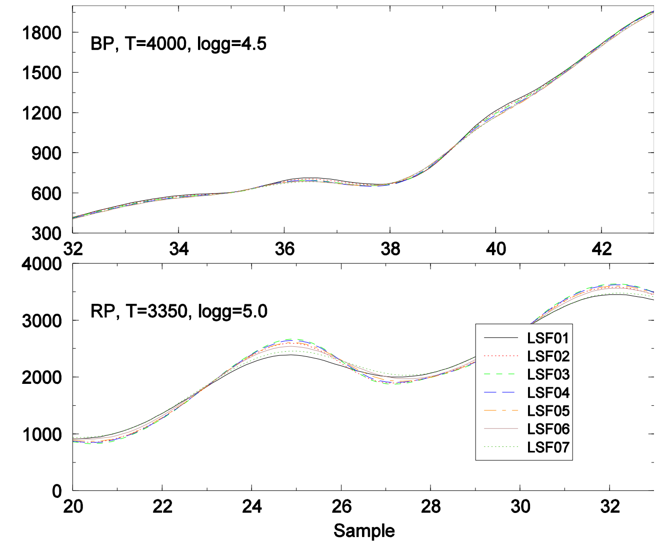
BP/RP processing: Dispersion and LSF



Disp effect

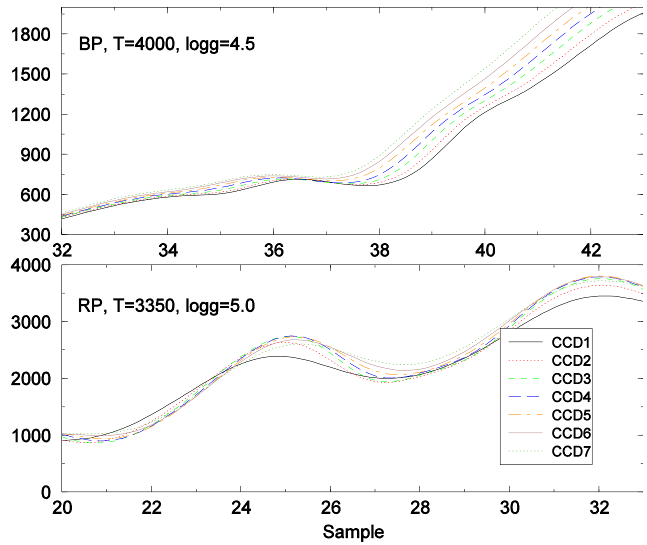
$D_7 \sim 0.9 D_1 \rightarrow \Delta\lambda_7 \sim 1.1 \Delta\lambda_1$

+



LSF effect

=



joint effect

Instrumental effects and calibration

UNITS OF CALIBRATION = "instrument"

- FoV
- Gate
- Window class
- AC position
- Time

INSTRUMENTAL EFFECTS

- Sensitivity (optics+CCDs)
- Aperture
- Background & straylight
- Gain, bias, CTI
- PSF/LSF (saturation)
- Contamination
- BP/RP blending
- Geometry
- Dispersion

Crowding

Crowding evaluation classifies BP/RP **transits** as "isolated", "contaminated" or "blended" and produces a mask indicating which samples can be used for background modelling.

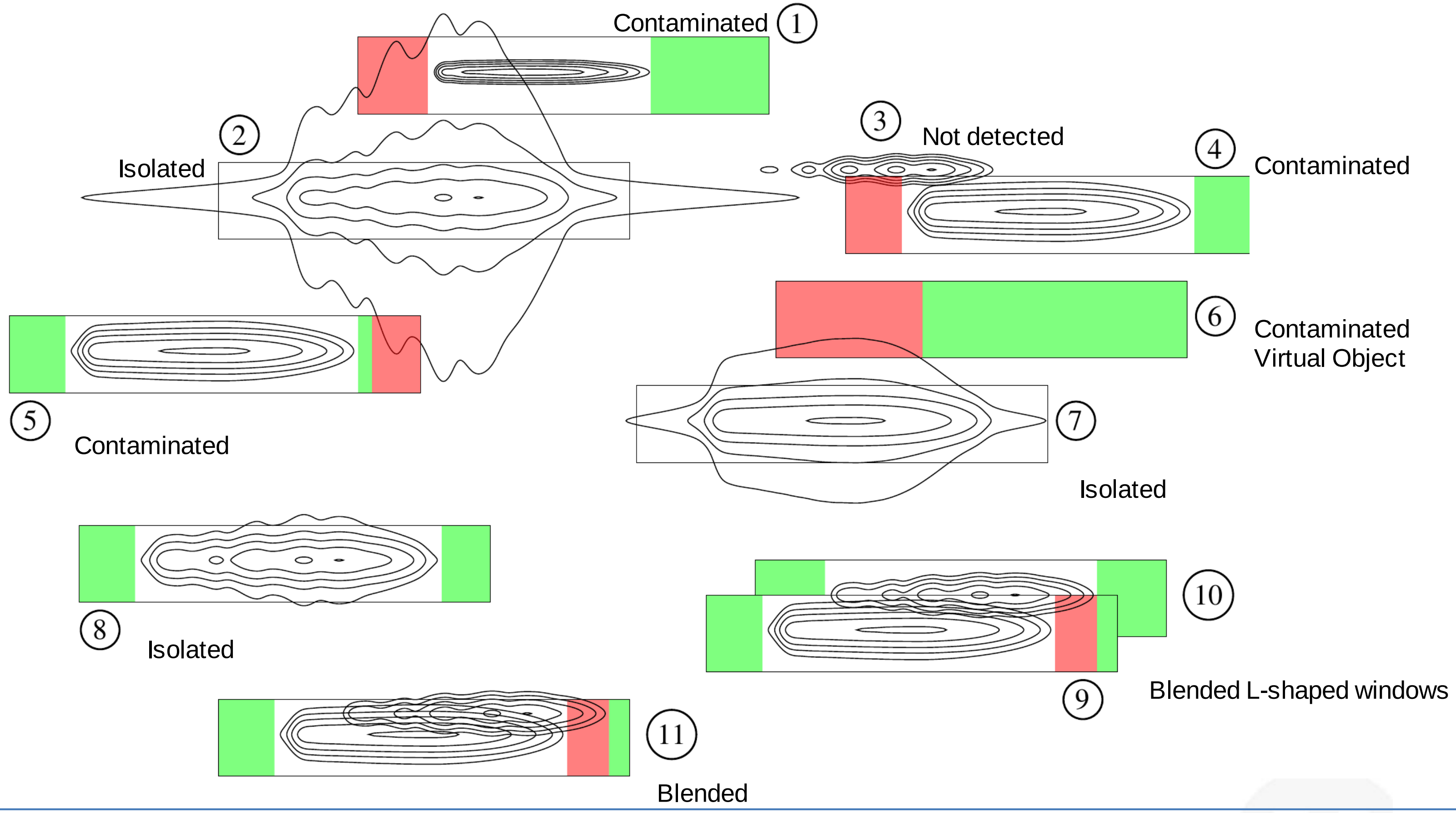


Figure courtesy Anthony Brown

Instrumental effects and calibration

UNITS OF CALIBRATION = "instrument"

- FoV
- Gate
- Window class
- AC position
- Time

INSTRUMENTAL EFFECTS

- Sensitivity (optics+CCDs)
- Aperture
- Background & straylight
- Gain, bias, CTI
- PSF/LSF (saturation)
- Contamination
- BP/RP blending
- Geometry
- Dispersion

It is unfeasible to have enough standard sources available

Calibration units in GDR1 (14 Sep 2016)

Large Scale (LS): CCD level. Daily basis
Small Scale (SS): Groups of columns. 14 months

Carrasco et al (2016)

Number of calibration units (CU) in DR1 (14 months)

Instrum.	Scale	N_{rows}	N_{strips}	$N_{gate/WC}$	N_{FoV}	N_{AC}	N_{time}	N_{CU}	
AF	LS	7	8/9	10	2	-	420	529 200	→ 1260 CU/day
AF	SS	7	8/9	10	-	492	1	309 960	
BP/RP	LS	7	1	6	2	-	420	35 280	→ 84 CU/day
BP/RP	SS	7	1	6	-	492	1	20 664	

Number of observations per CU in GDR1 (using all sources):

Instrum.	Window	Gate	t_{exp} (s)	G range	N_{obs}^{LS}	N_{obs}^{SS}
AF	WC0	Gate04	0.02	$G < 8.5$	300	400
AF	WC0	Gate07	0.13	8.5–9.5	300	450
AF	WC0	Gate08	0.25	9.5–10.0	600	1000
AF	WC0	Gate09	0.50	10.0–11.0	700	1100
AF	WC0	Gate10	1.00	11.0–12.0	1900	3000
AF	WC0	Gate11	2.01	12.0–12.2	1000	1200
AF	WC0	Gate12	2.85	12.2–12.4	1800	2500
AF	WC0	None	4.41	12.4–13.0	12 000	23 000
AF	WC1	None	4.41	13.0–16.0	150 000	290 000
AF	WC2	None	4.41	$G > 16.0$	2 200 000	3 600 000

Principles of processing: self-calibration

Variety of "**instruments**":

CCDs, columns, telescopes, …

Variety of **configurations**:

1D, 2D, narrow & large windows, gates, …

Variety of **sources** to be observed (stars, galaxies, QSO, SSO, SNe, …) with different configurations

Time variations of both sources and instrument through the mission (5 years)

Ubercalibration: Relative calibration of differences among instruments and configurations. All "well-behaved" sources can be used as internal standards

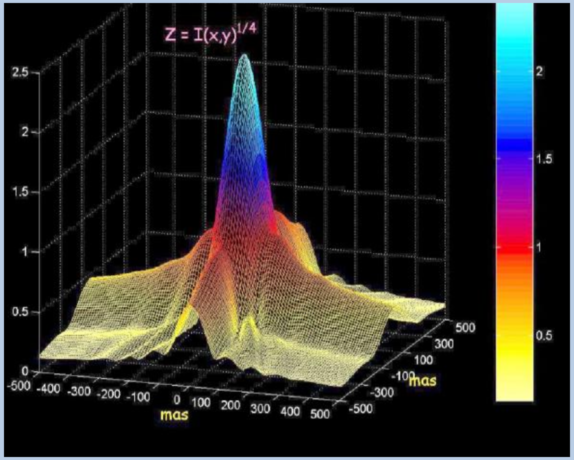
1 billion sources

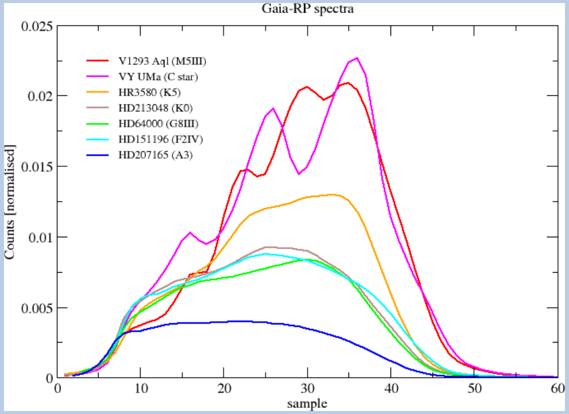
If only 10% are "well-behaved" → 100 million sources as standards

Absolute calibration through relatively 100-200 ground-based standards

PhotPipe

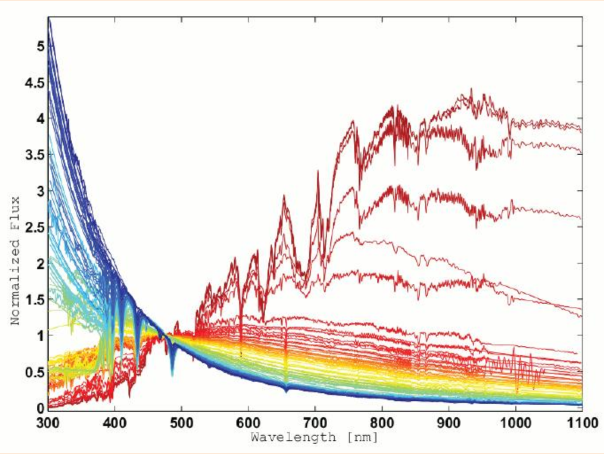
Observations



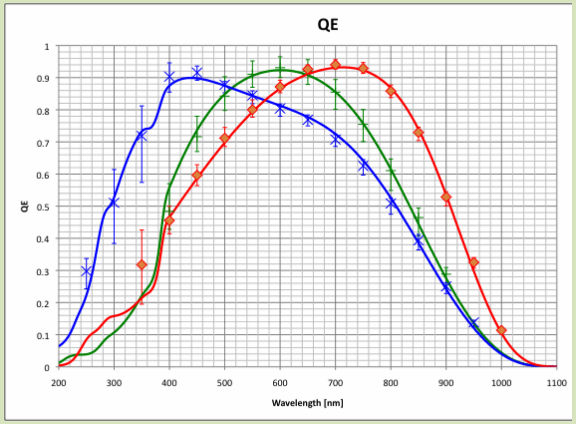


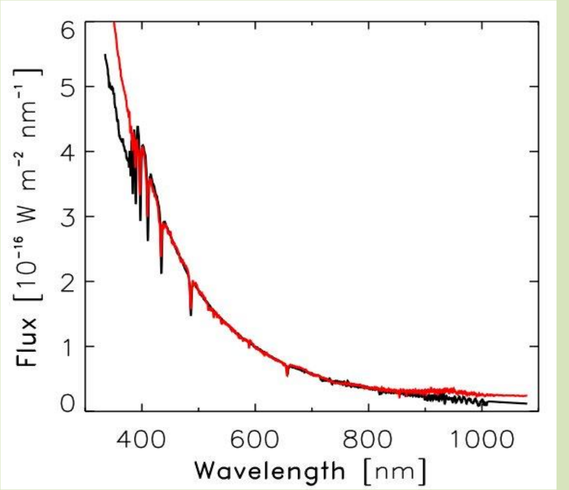
Calibration

- Internal calibrators
  millions of sources
- External calibrators
  ~ 200 SPSS
  (Pancino et al 2012)



Output





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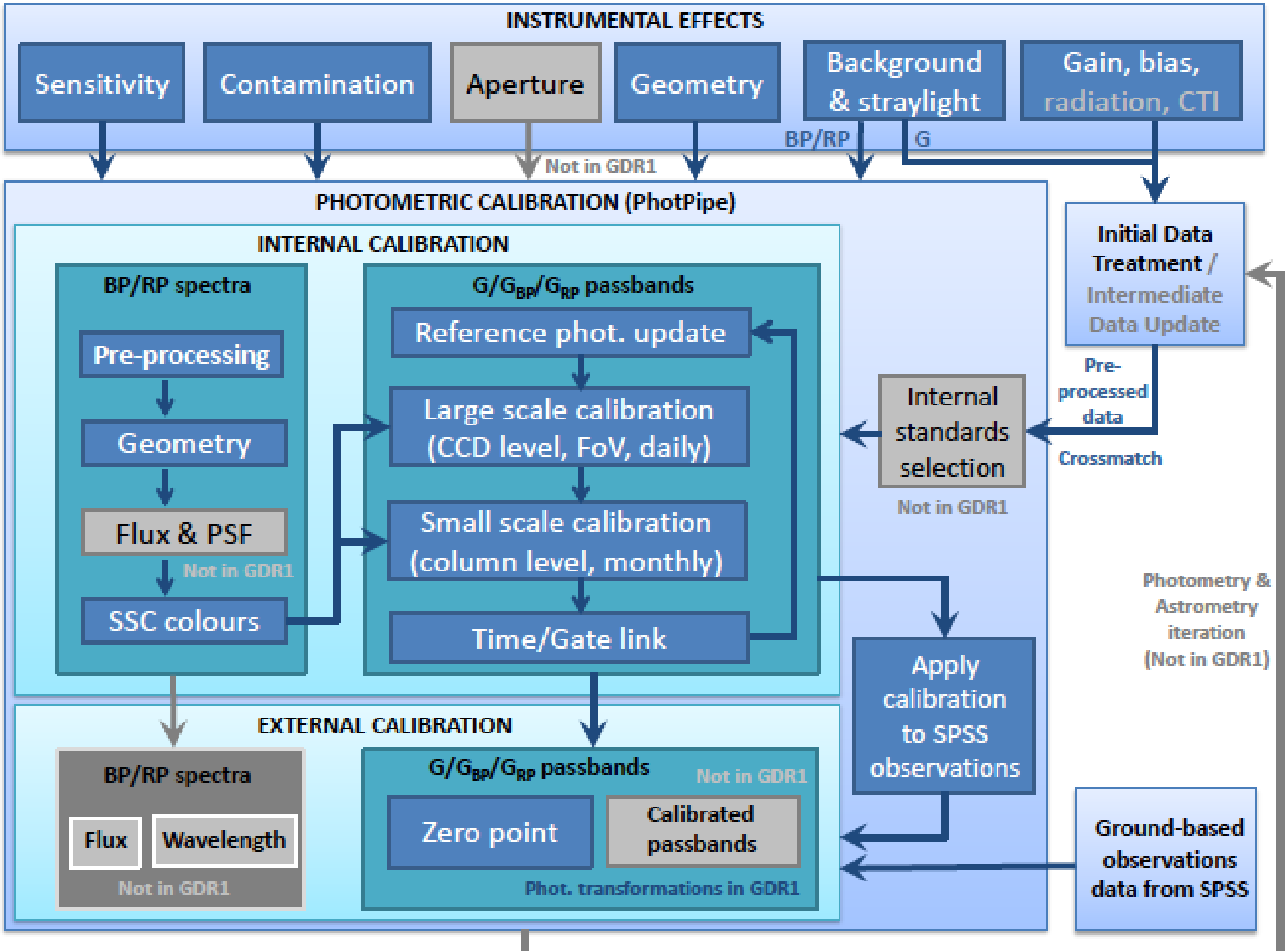
PhotPipe structure



Photometric Alerts

Carrasco et al (2016)

Passband internal calibration in GDR1

Initialization: $\overline{I_s} = \sum_k I_{sk} \frac{w_k}{\sum_k w_k}$

	Equation Limits	N_{coefs}	Coefficients
LS	$R = 1,\ M = 6,\ J = 2$	9	$A_{11l}, A_{12l}, A_{13l}, A_{14l}, A_{15l}, A_{16l}, B_{0l}, B_{1l}, B_{2l}$
SS	$R' = 0,\ M' = 1$	1	$a_{01l'}$

Selection of internal standard sources:

constant sources (all sky, all colours, all types, full range of magnitudes)

Calibration:

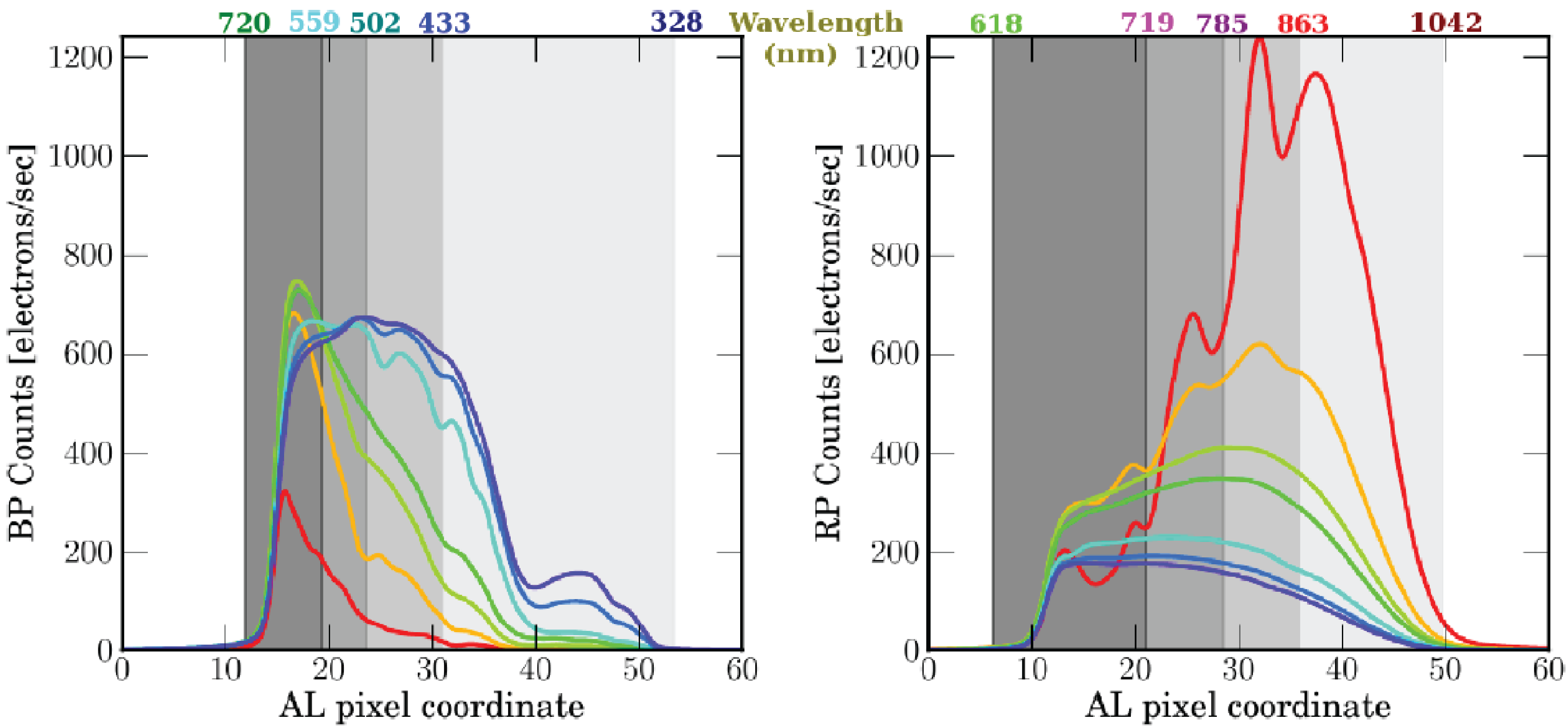
$$\frac{I_{skll'}}{\overline{I_s}} = \mathrm{LS}_{skl} \cdot \mathrm{SS}_{skl'} \quad \begin{cases} \mathrm{LS}_{skl} = \sum_{r=1}^{R} \sum_{m=1}^{M} A_{rml} \cdot (C_{sm})^r + \sum_{j=0}^{J} B_{jl} \cdot (\mu_k)^j \\ \mathrm{SS}_{skl'} = \sum_{r=0}^{R'} \sum_{m=1}^{M'} a_{rml'} \cdot (C_{sm})^r \end{cases}$$

Source update: $\overline{I_s} = \sum_k I_{sk} \frac{w_k}{\sum_k w_k} \Big/ \mathrm{LS}_{skl} \cdot \mathrm{SS}_{skl'}$

Carrasco et al (2016)

Colour dependence

Colour dependence calibrated with Spectral Shape Coefficients
Linear terms for dependences



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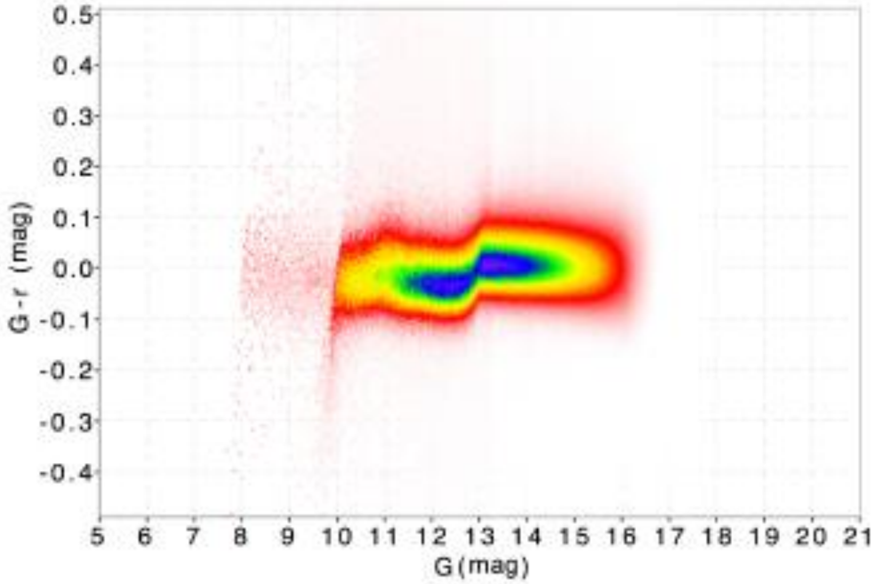
Mixing

- The several calibration units (CUs) are treated separately
- Every CU potentially defines a photometric instrument/system
- To converge to a unique ”mean” instrument, one needs a large amount of sources observed with different CUs
- If there is poor mixing, there will be differences among the several CUs

For DR1 (only 14 months with some gaps), we introduced additional steps:

- Gate/window link (to account for poor mixing)
- Time link (to account for decontamination events)

Gate/window link



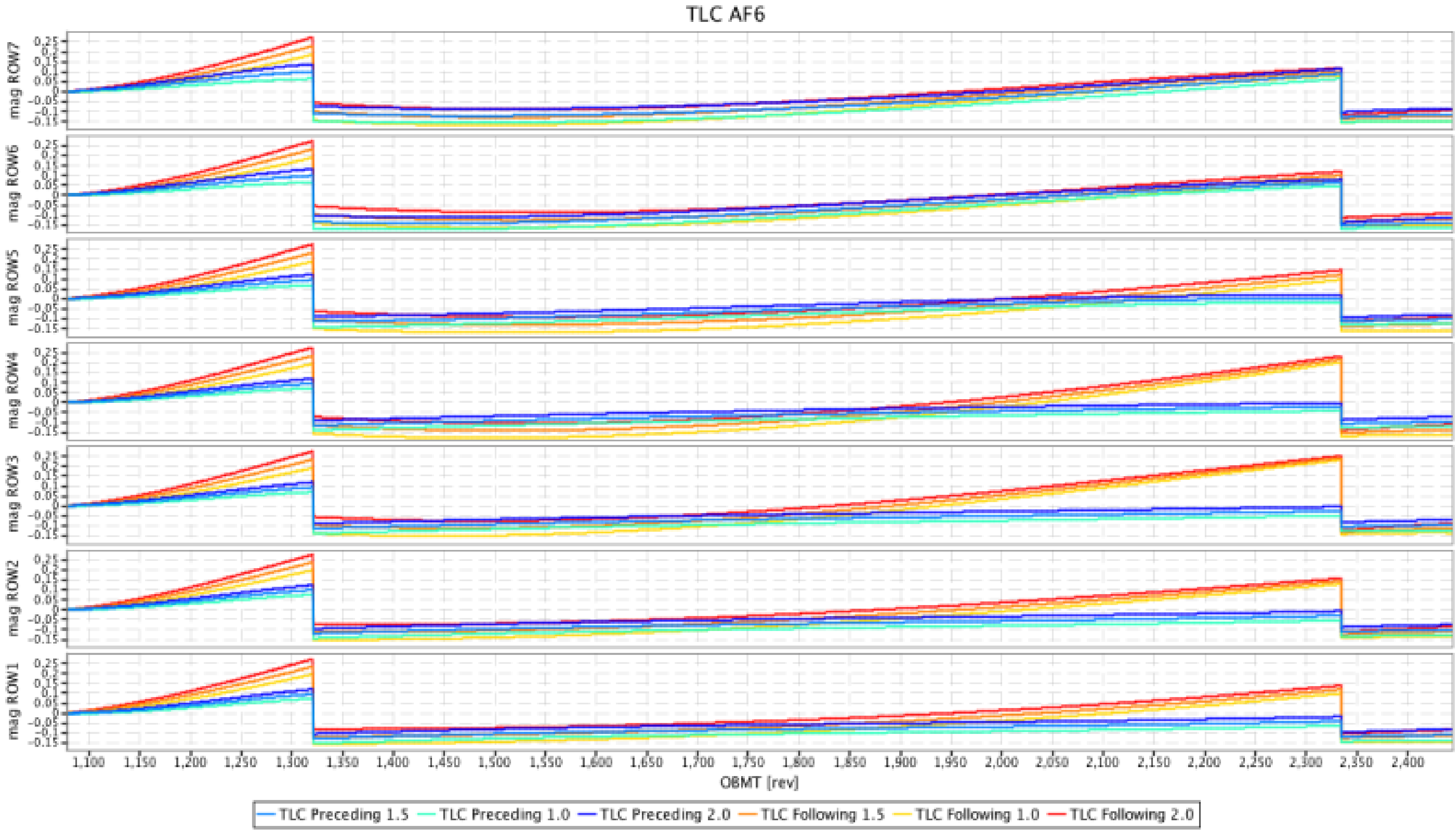
Before calibration

At G=13, acquisition windows change from 2D (PSF fitting) to 1D (LSF fitting)

After calibration

Carrasco et al (2016)

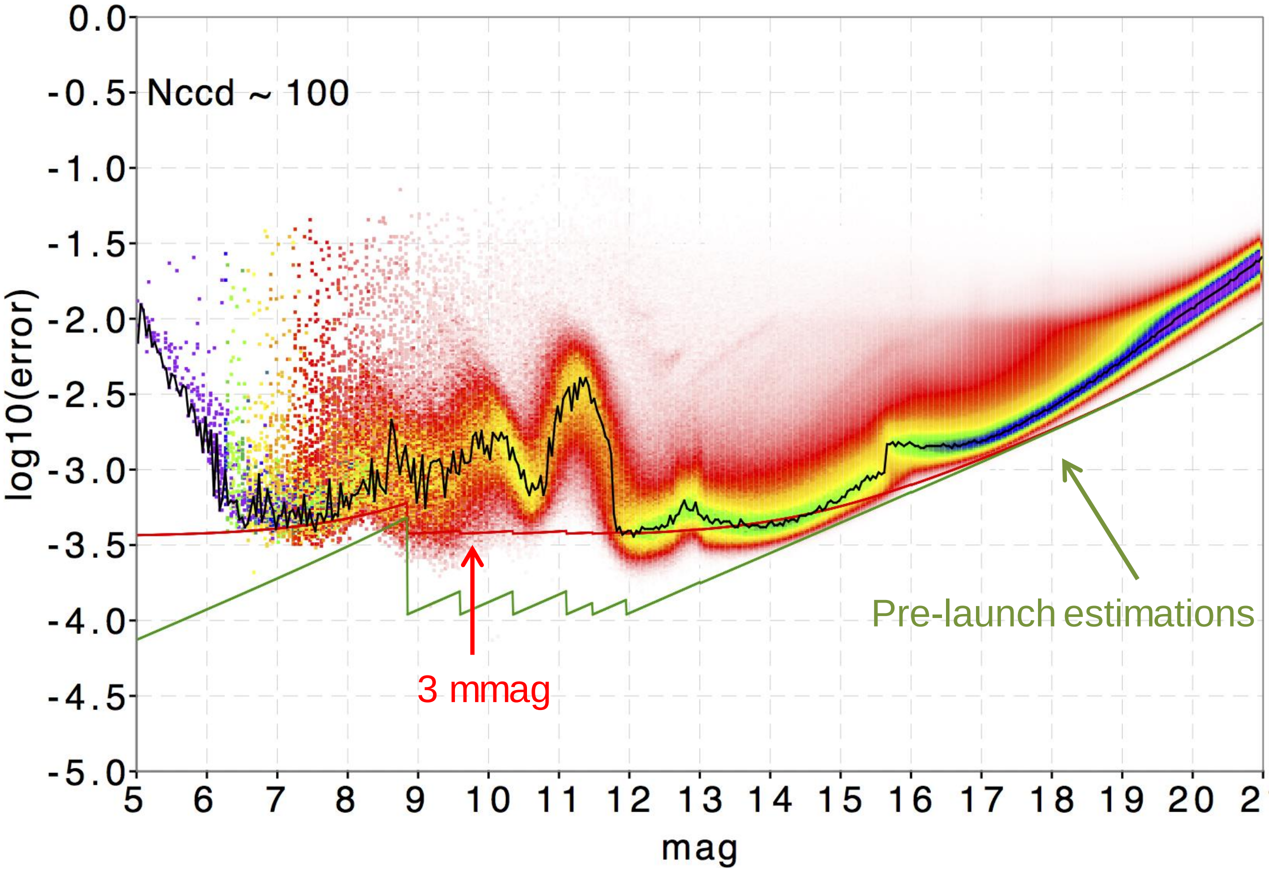
Time link (contamination)



Riello et al (in prep)

Gaia-DR1: photometry

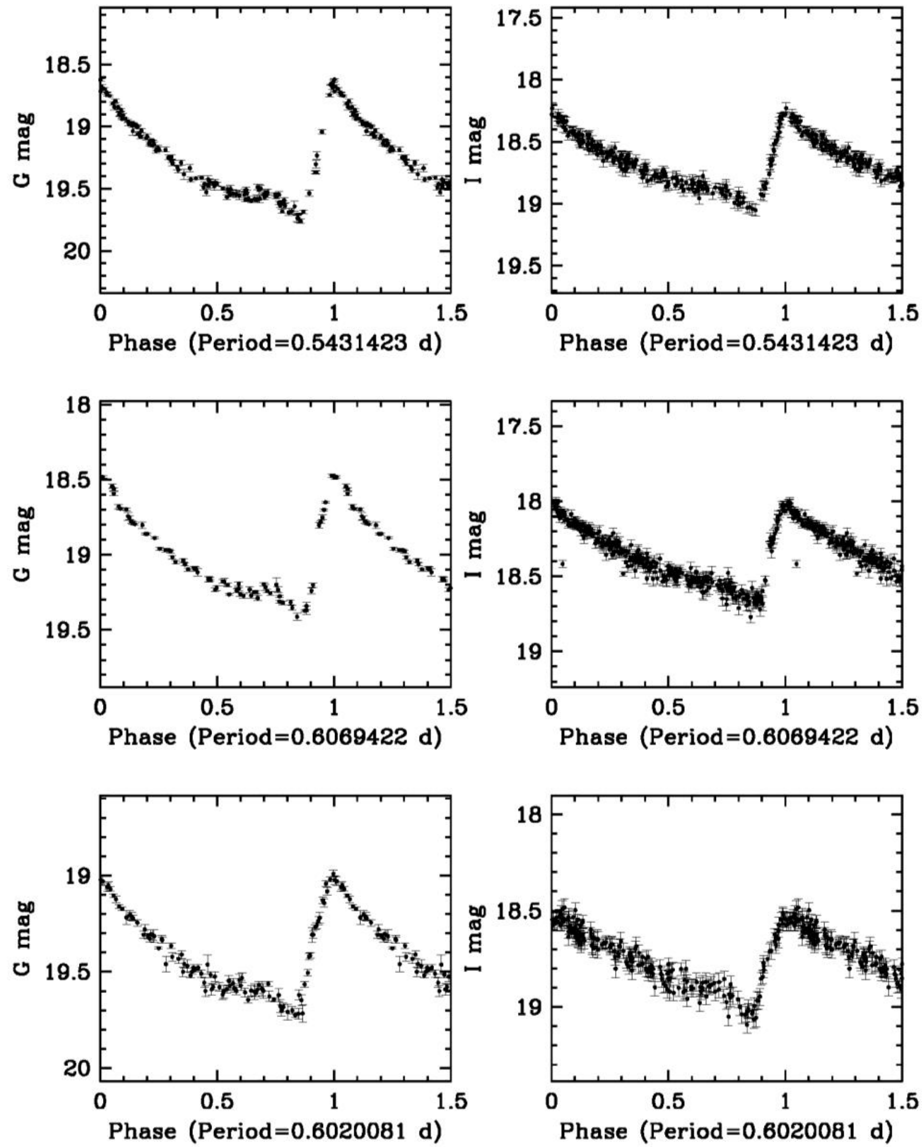
Error on the weighted mean G value for a source with ~100 CCD transits



- Systematics of ~10 mmag (comparison with external catalogues)
- Science performances: Gaia webpage

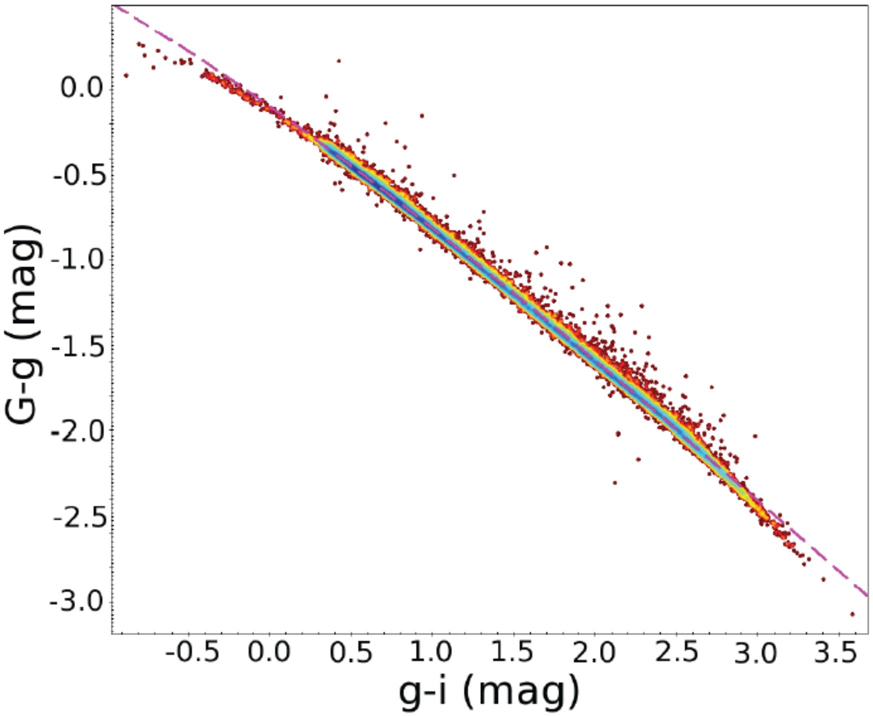
Evans et al (2016)

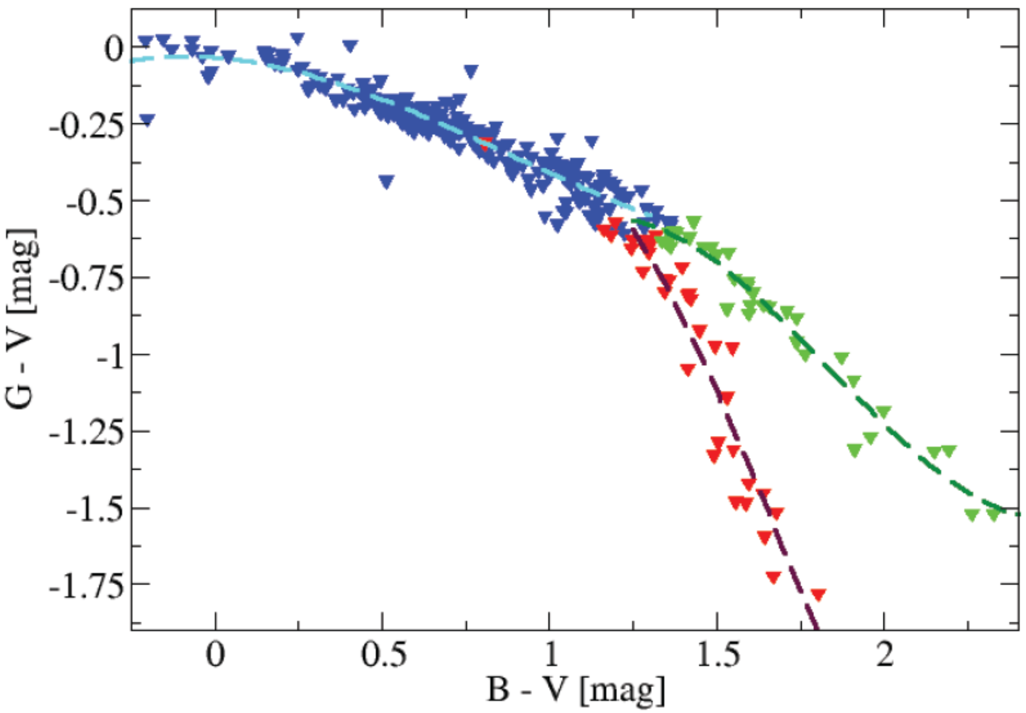
Gaia-DR1: photometry



RR Lyrae
(RRab)

Gaia-DR1: Photometric transformations

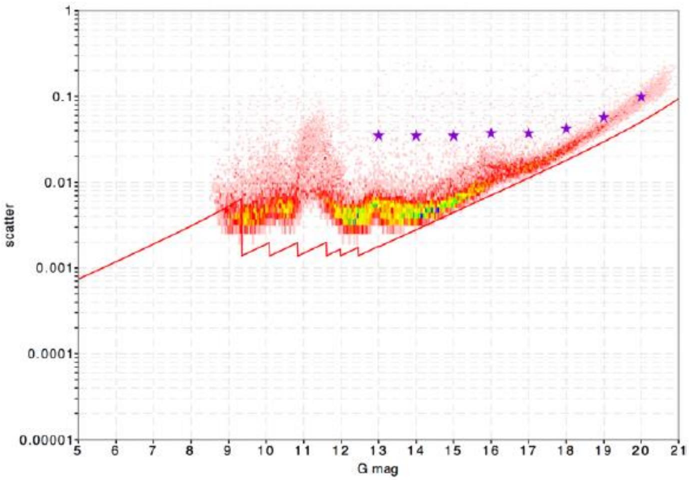




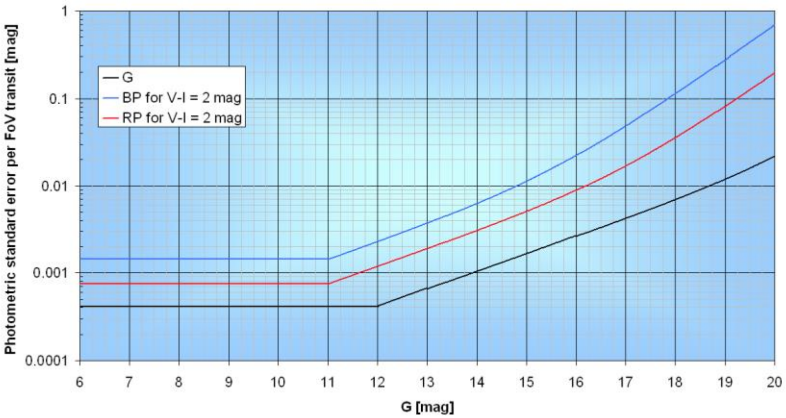
Photometric relationships with SDSS, Johnson, Hipparcos, Tycho and HST are provided in Gaia-DR1.

Carrasco et al (2016)

Data releases scenario

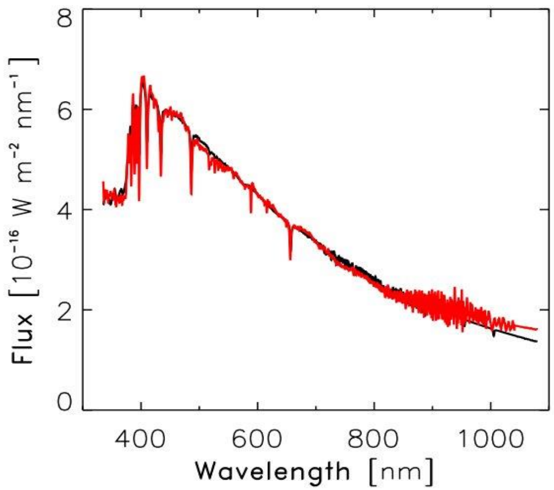


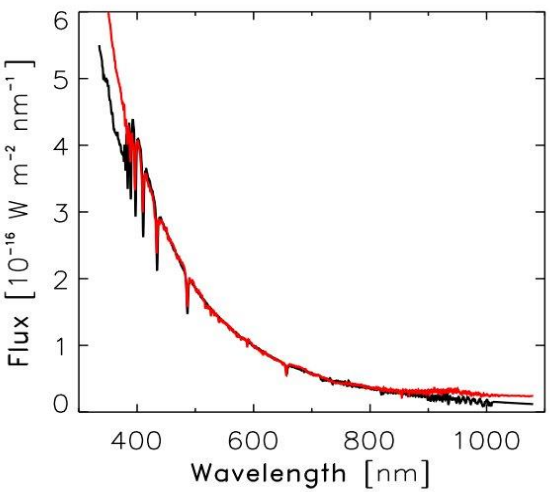
First release, 14th Sep 2016
G passband



Second release, Q4-2017
G_{XP} passbands

Third release 2018 (TBC)
XP spectra



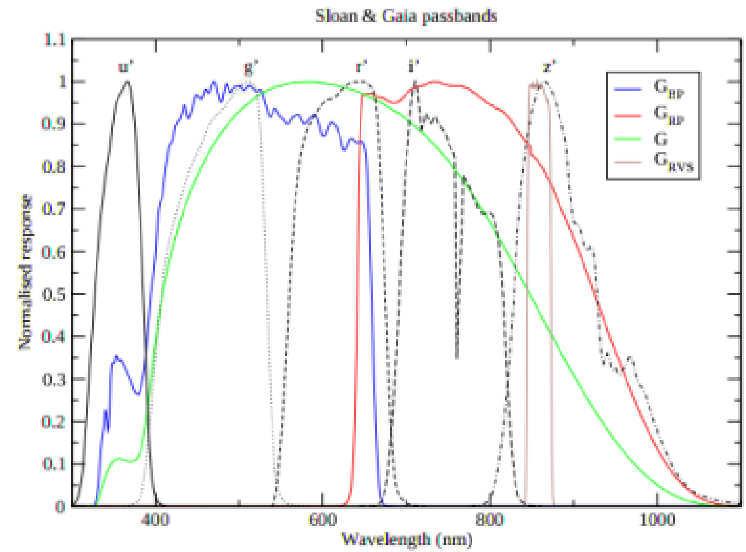


Synthetic photometry

We use FAIM (Functional Analytic Instrument Model) formalism

F: Synthetic flux in the passband **T: Passband transmissivity** **s: Calibrated SED of the source**

$$F = \int_{\lambda_0}^{\lambda_1} T(\lambda) \cdot s(\lambda)\,\mathrm{d}\lambda$$

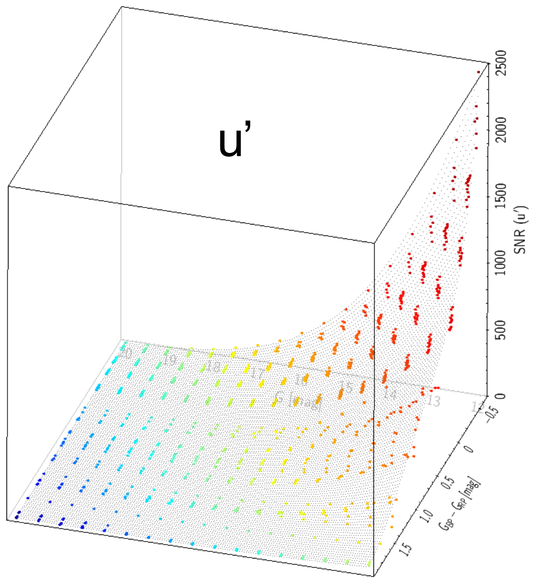


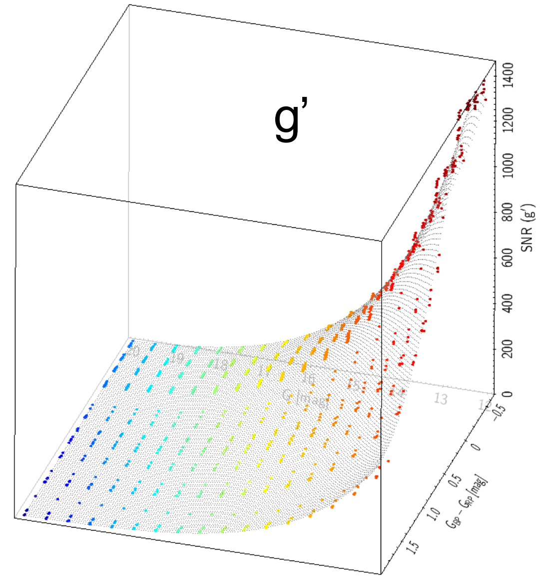
Covariance matrix of the vector s: Σ^{s}

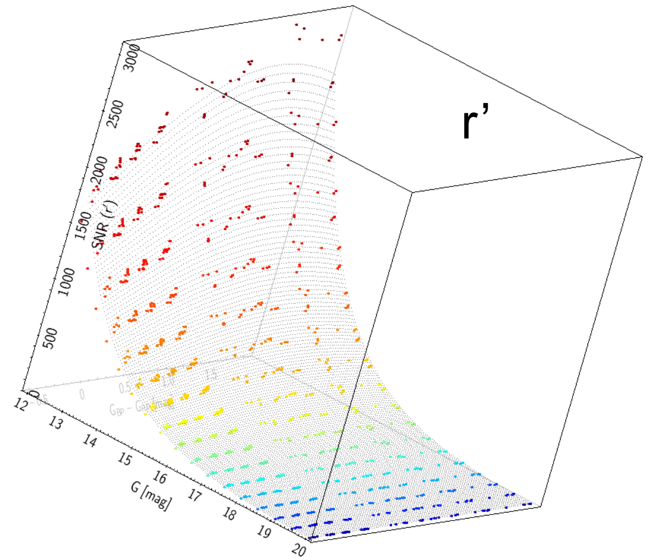
↓

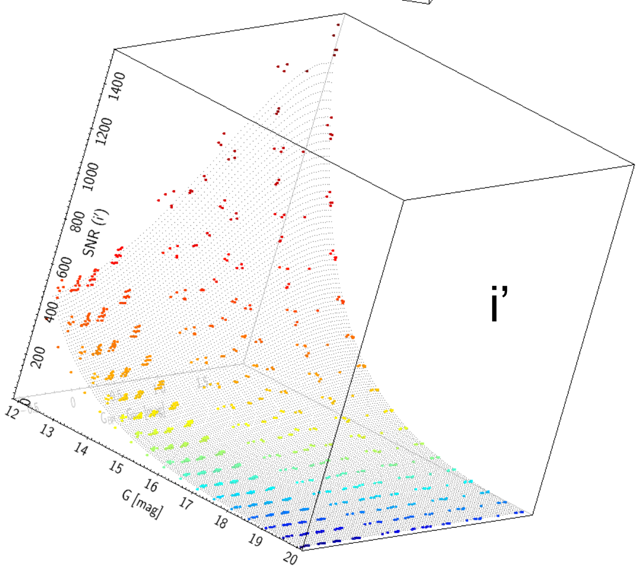
Variance of the flux in the passband : Σ^{F} ⟶ SNR = F / Σ^{F}

Example of Synthetic photometry: SDSS

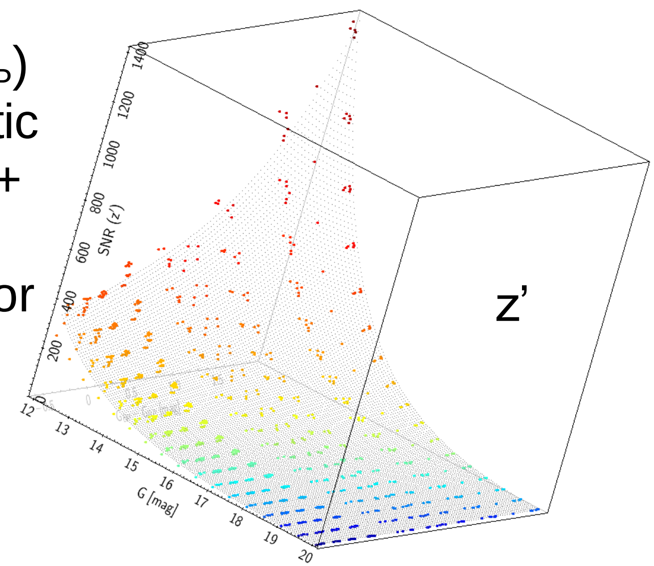






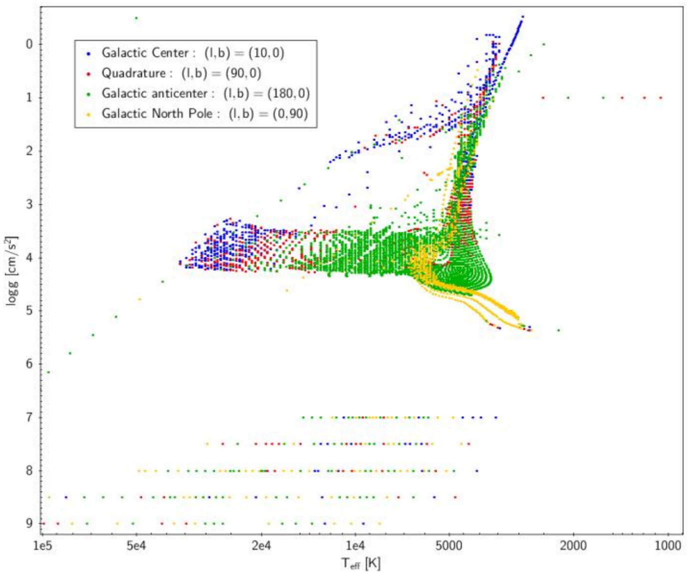


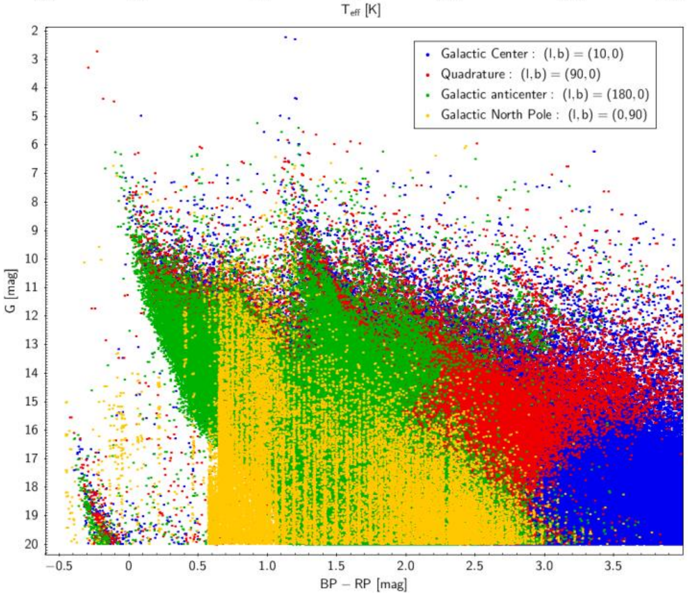
Fitted $SNR_x = f(G, G_{BP} - G_{RP})$ relationships from synthetic photometry (BaSeL-3.1 + WDs) will be made available in GOG simulator (SDSS, Johnson, Hipparcos/Tycho, …)



Gaia Universe Model Snapshot

Robin et al (2012)





Stars with G<20 for a FoV=4º

- Galactic center: *l*=10º *b*= 0º
- Quadrature: l=90º, b=0º
- Anticenter: l=180º, b=0º
- Galactic North Pole: l=0º, b=90º

G	ρ_{center} (star/deg²)	$\rho_{quadrature}$ (star/deg²)	$\rho_{anticenter}$ (star/deg²)	ρ_{pole} (star/deg²)
<16	15766	17256	9052	454
16-17	15231	17167	6857	271
17-18	27295	28527	10921	407
18-19	48206	46642	15676	607
19-20	81088	76598	20832	868
All	187586	186204	63338	2607

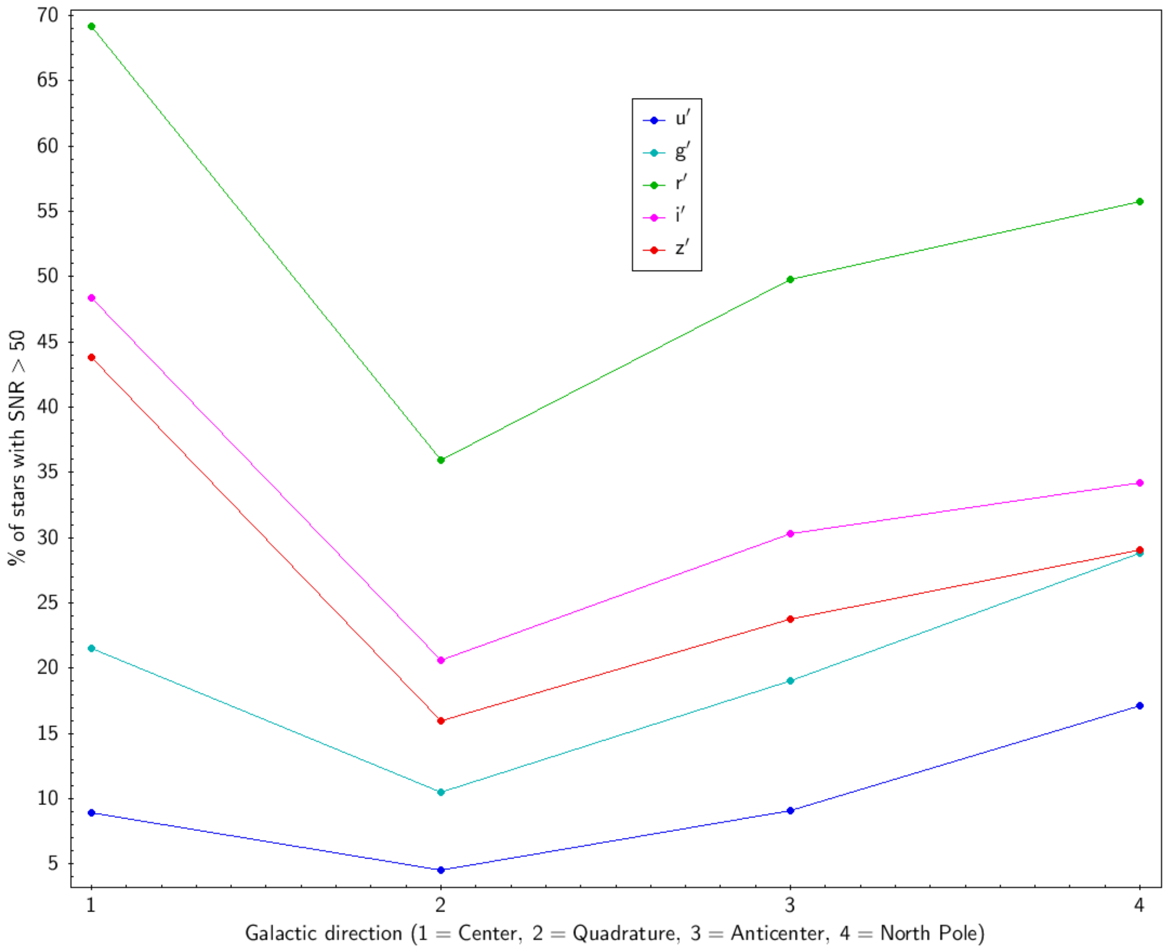
SNR for the simulated sample

12<G<20,
-0.63<G_{BP}-G_{RP}<1.95

Galactic North Pole:
l=0º, b=90º

Filter	%	Stars/deg²
u'	17	443
g'	29	756
r'	56	1460
i'	34	886
z'	29	756

Stars with SNR>50



Conclusion: Gaia photometry is unique

- Gaia is not only very good astrometry
- Gaia is an homogeneous all-sky coverage
  10^9 sources with $G_{\text{lim}} \sim 20.5$
- Integrated photometry (G, G_{BP} and G_{RP} passbands)
  End-of-mission uncertainty at mmag level
- Spectrophotometry down to G_{lim} → Physical parameters
- Variability detection (G-band, 5 years)
- Space angular resolution
- Absolute calibration at 1% level accuracy

Gaia will be a wonderful source of good quality photometric standards for future projects (LSST, Euclid, J-PAS, …)

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Thanks

More information in A&A Gaia-Release 1 special volume (2016)

- Gaia Mission & 1st release: Gaia Collaboration (2016)
- Photometric Calibration: Carrasco et al (2016)
- Initial Data Treatment: Fabricius et al (2016)
- Gaia CCDs: Crowley et al (2016)

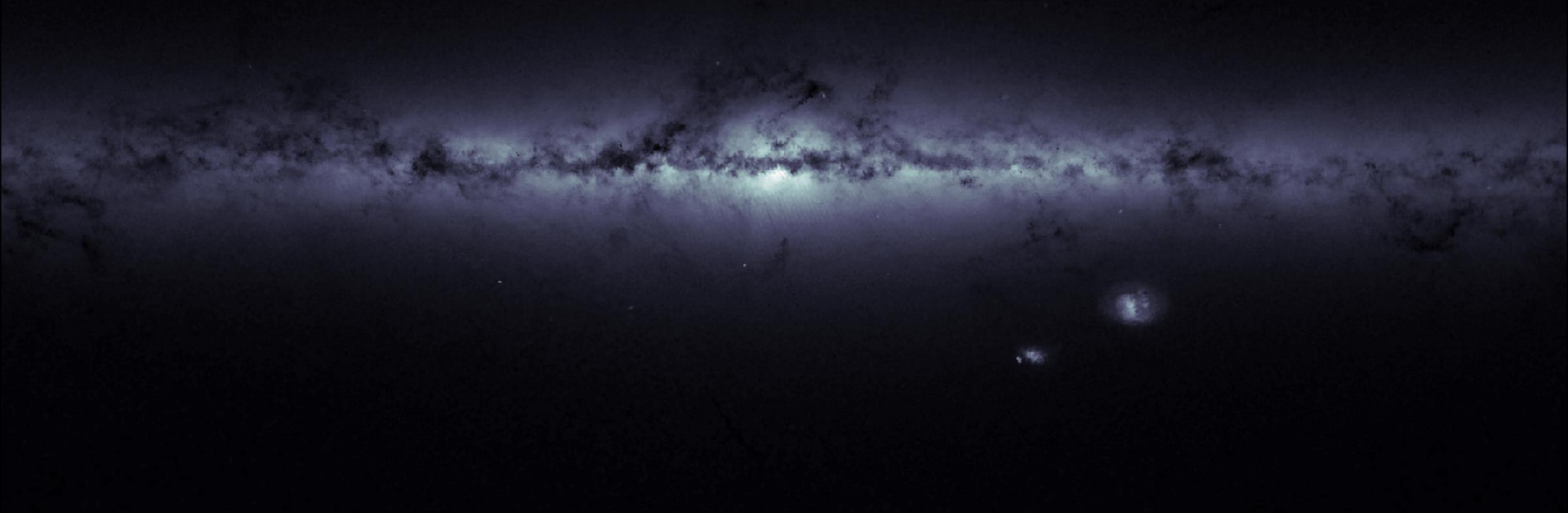

Fig: ESA/Gaia-CC BY-SA 3.0 IGO