Photometric Calibration of HST/WFC3

Susana Deustua
Space Telescope Science Institute
Baltimore, MD

And the Photometry Team

J. Mack, A.S. Bowers,

S. Baggett, V. Bajaj,

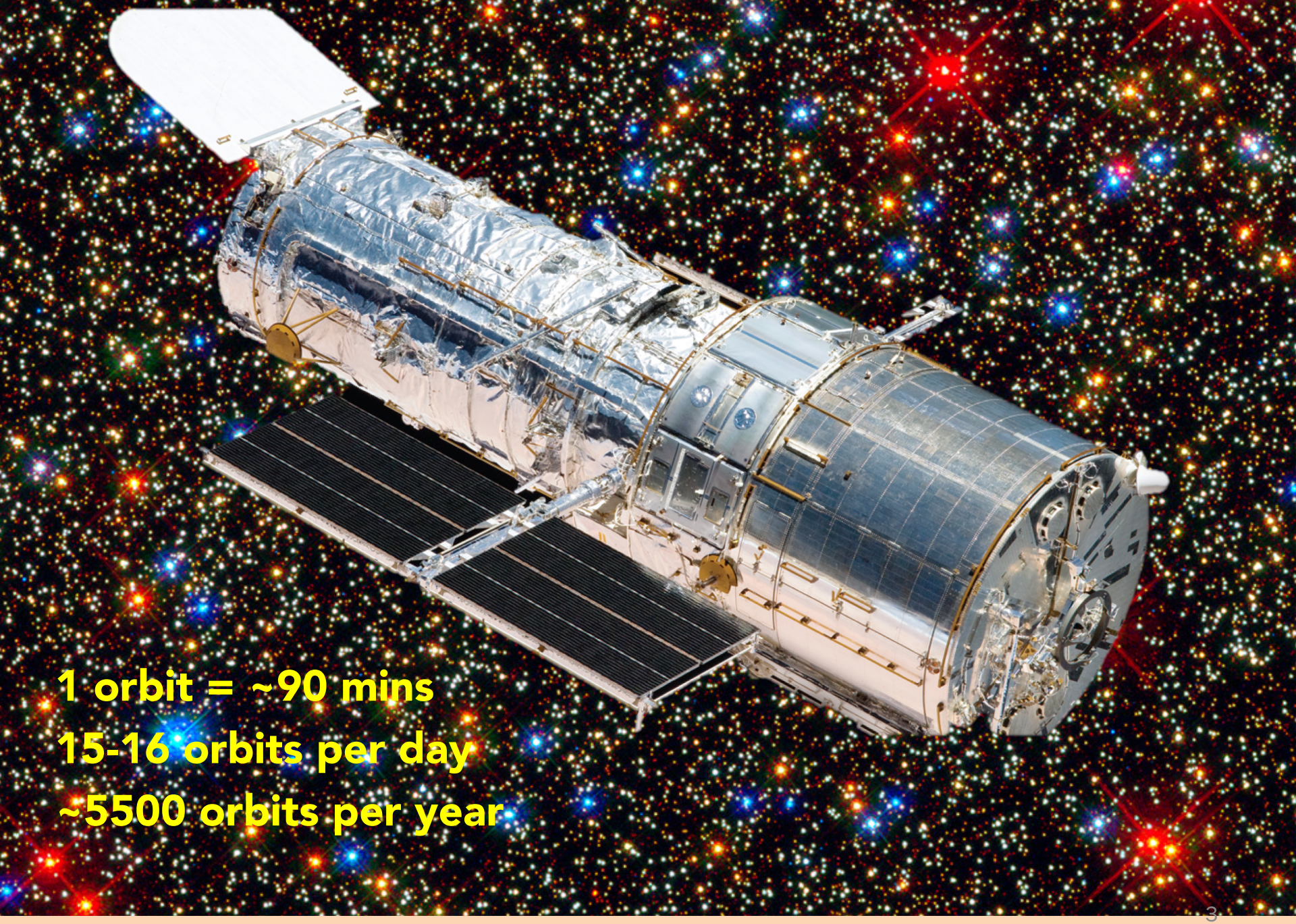
T. Dahlen, M. Durbin,

C. Gosmeyer, H. Gunning,

D. Hammer, G. Hartig,

H. Khandrika, J. MacKenty,

R. Ryan, E. Sabbi, M. Sosey


1 orbit = ~90 mins
15-16 orbits per day
~5500 orbits per year

S125E007372

WFC3 in Summary

WFC3/UVIS Channel

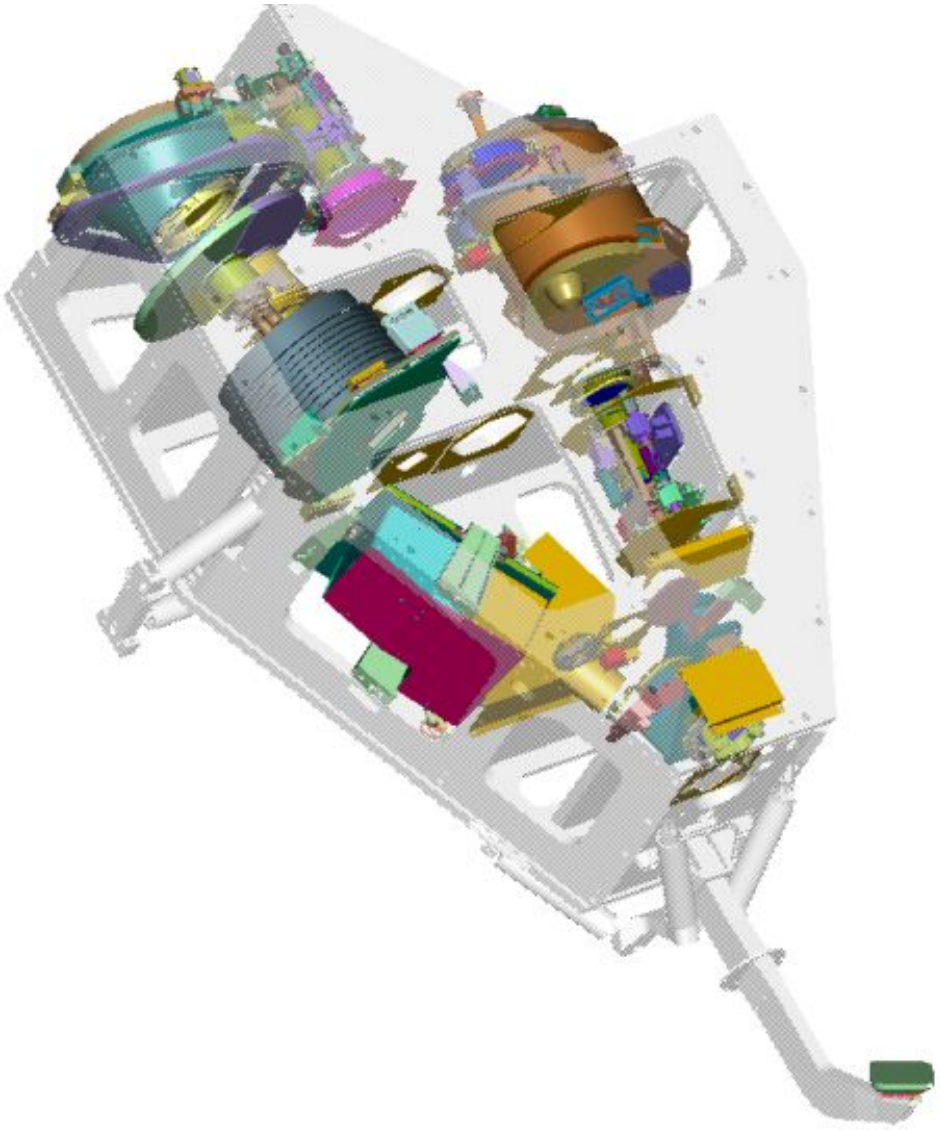
- 0.2 – 1.0 microns
- 2 4kx4k e2v CCDs, 0.04”/pix
- 62 filters + 1 grism
- 12 subarray options

WFC3/IR Channel

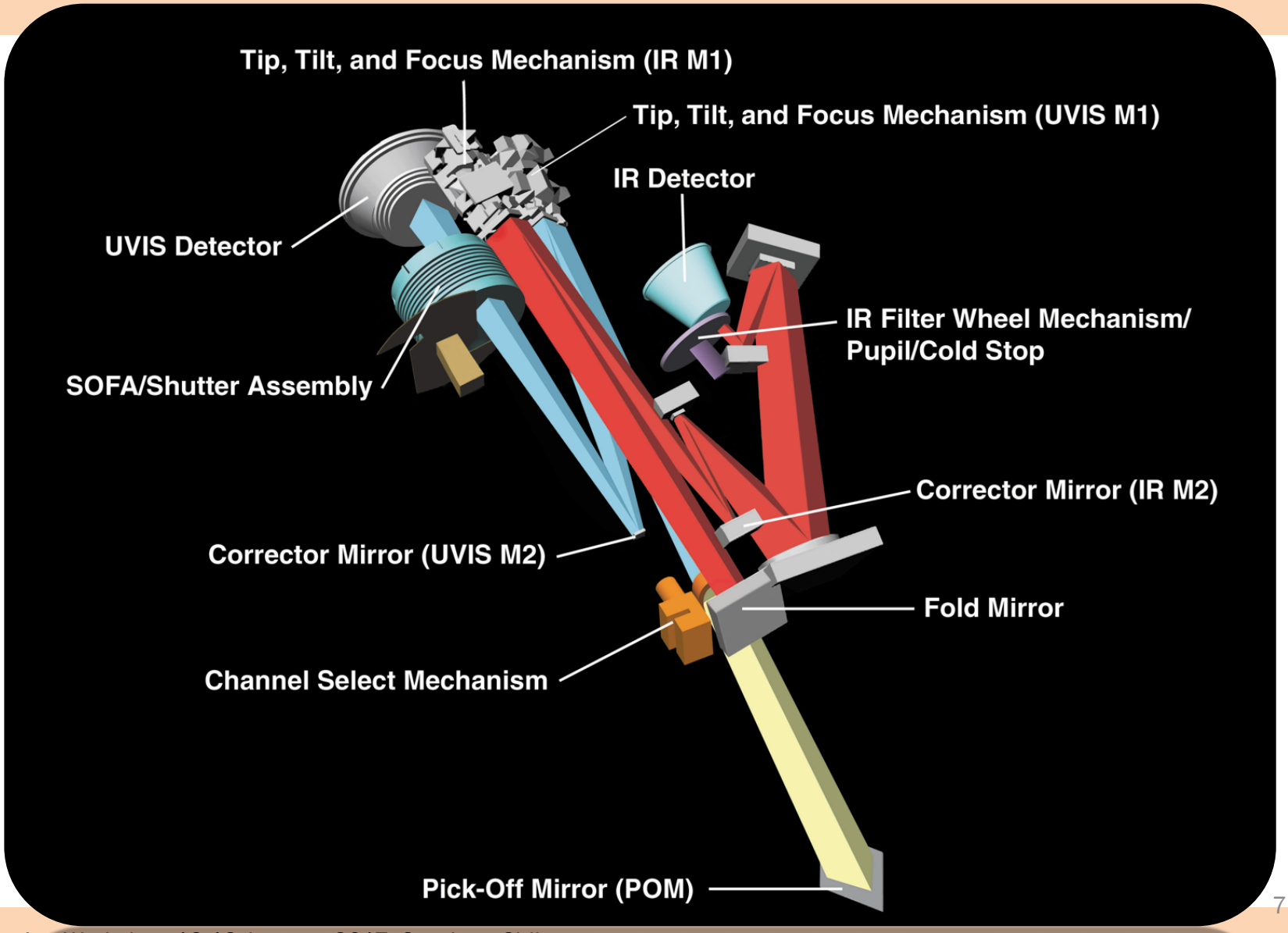
- 0.9 – 1.7 microns
- 1kx1k H1RG MCT, 0.13”/pix
- 15 filters + 2 grisms
- 5 subarray options

Observing modes:
Stare: UVIS and IR imaging and spectroscopy
Scan: UVIS and IR imaging, IR spectroscopy, up to 7”/sec

WFC3 Optical Layout



WFC3 Optical Layout



Calibration Allocation

Time spent on calibration activities per cycle (averages)

- External orbit: on astrophysical sources
- Internal orbit: during occultation.
- 1 orbit ~ 45 min

Instrument: external/internal

WFC3: 100/2000

ACS: 30/1000

STIS: 30/1400

COS: 40/320

HST Cycle	GO Programs* % of HST orbits	Calibration** # External orbits	Calibration** # Internal orbits
CY17	46%	256	>2000
CY18	42%	134	1719
CY19	49%	125	1497
CY20	56%	83	1833
CY21	54%	98	1907
CY22	48%	114	1620
CY23	46%	98	1619
CY24	**40%**	**69**	**1557**

WFC3 Calibration Orbits Since 2009

* excluding SNAP, MCT, Frontier Fields

** midcycle calibration programs excluded

Typical Calibration Plan

- UVIS: bias, dark, gain stability, bowtie, anneals, CTE, sink pixels, traps
- IR: linearity, dark, gain, persistence
- Photometric: flux calibration, flat fields, contamination
- Spectroscopic: wavelength and flux calibration
- Astrometric
- Other: e.g. non-linearity tests, new techniques, model testing

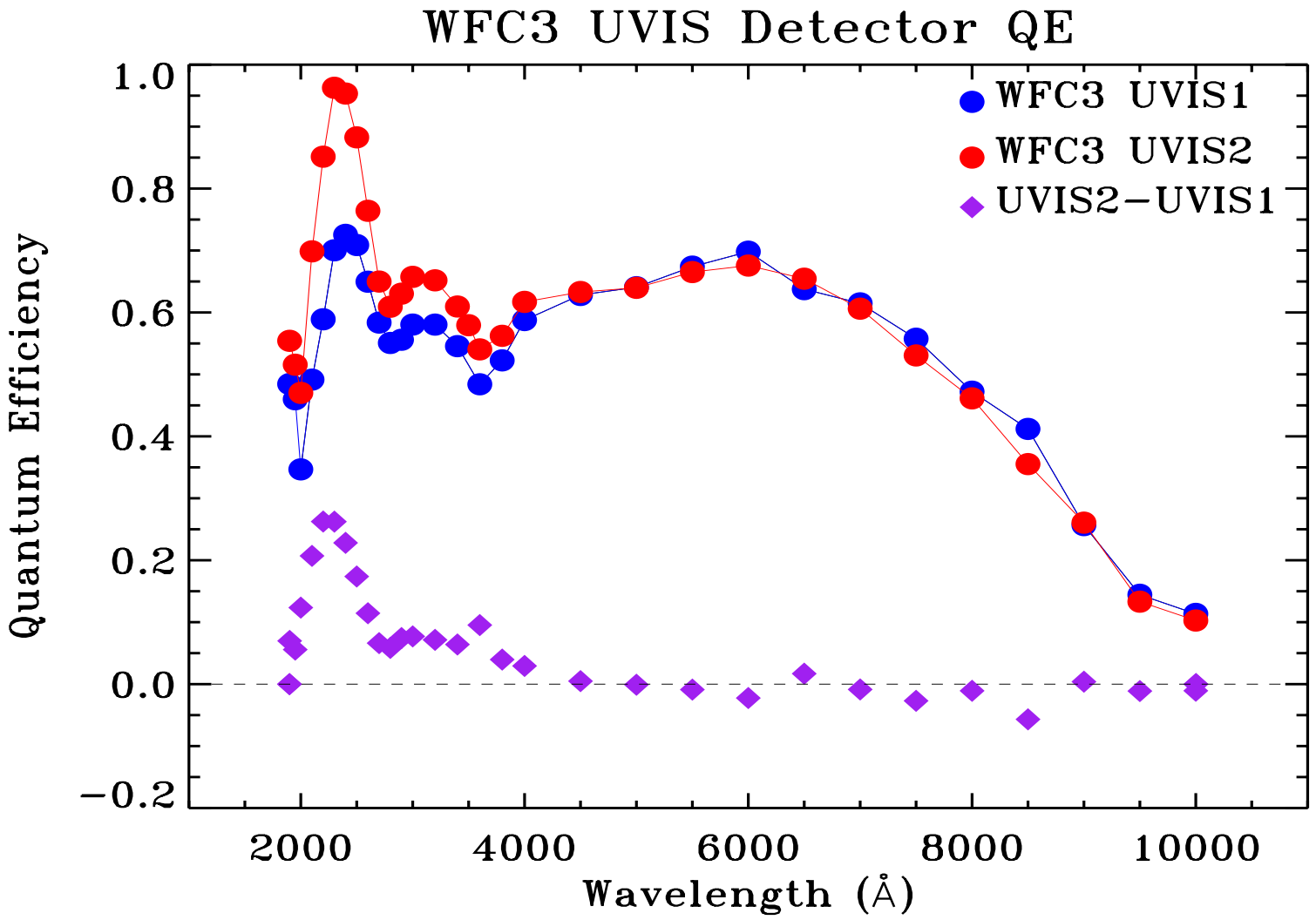
Principal UVIS Detector Effects

- **CCD Charge Transfer Efficiency (CTE, or CTI)**
  - **Most affected:**
    - **Sources furthest from readout**
    - **Faint sources, can "disappear"**
    - **All CCD detectors on HST**
  - **Effect: bright stars < 0.1%, faint sources larger**
  - **Mitigation:**
    - **Post-Flash (add background e- to fill traps)**
    - **Place science targets near readouts.**

Calibration Pipeline

- CALWF3: bias & dark subtraction, flat fielding, CTE correction & Flash correction (UVIS), linearity correction (IR), up-the-ramp fit (IR), populates header keywords
- AstroDrizzle: applies geometric distortion, combines images from a visit.
- Calibration Products
  - UVIS: FLT, FLC, DRZ, DRC
  - IR: IMA, FLT, DRZ

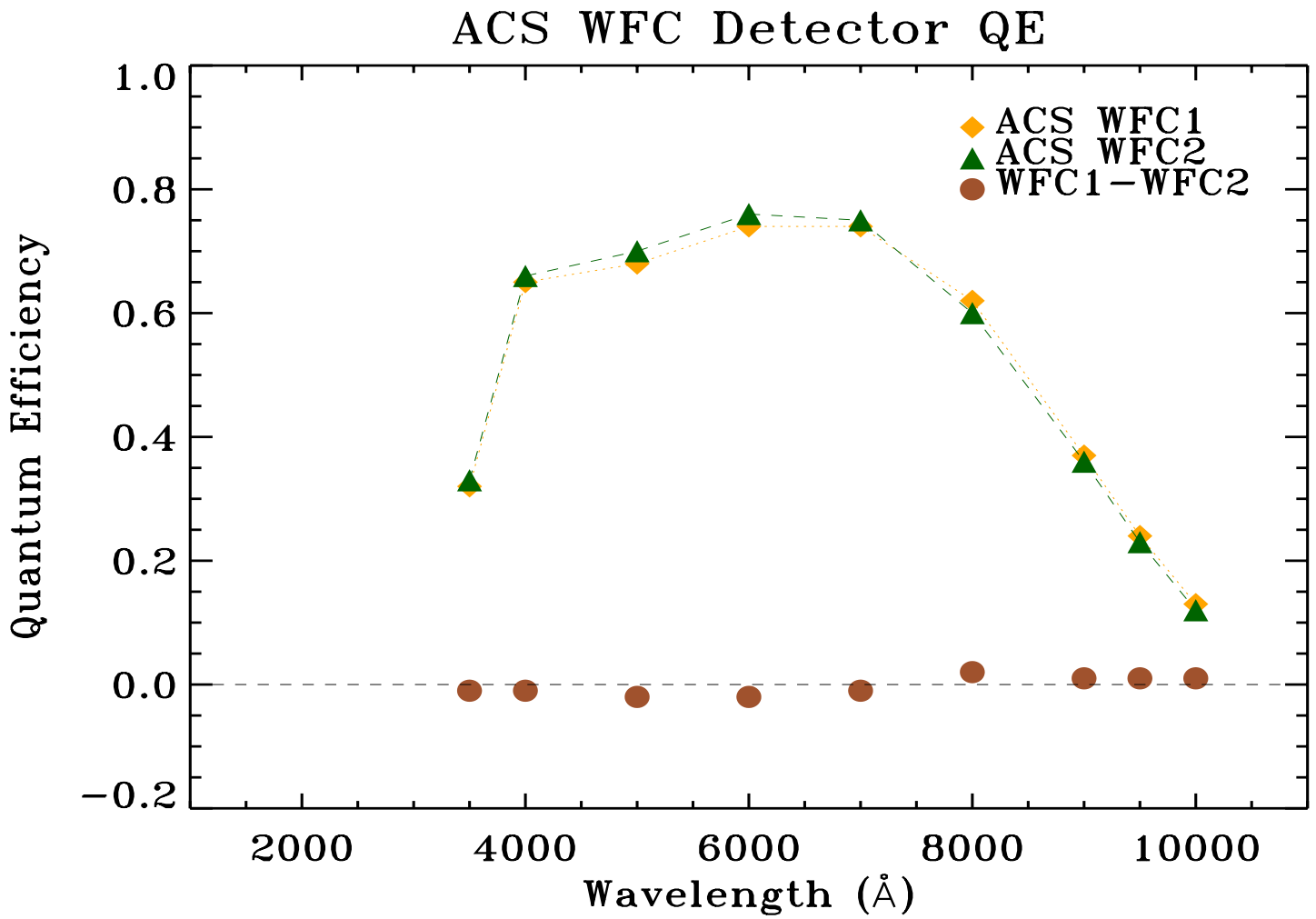
WFC3/UVIS


WFC3 UVIS Detector QE
WFC3 UVIS1
WFC3 UVIS2
UVIS2−UVIS1
Quantum Efficiency
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
2000
4000
6000
8000
10000
Wavelength (Å)

Inverse Sensitivity (response)

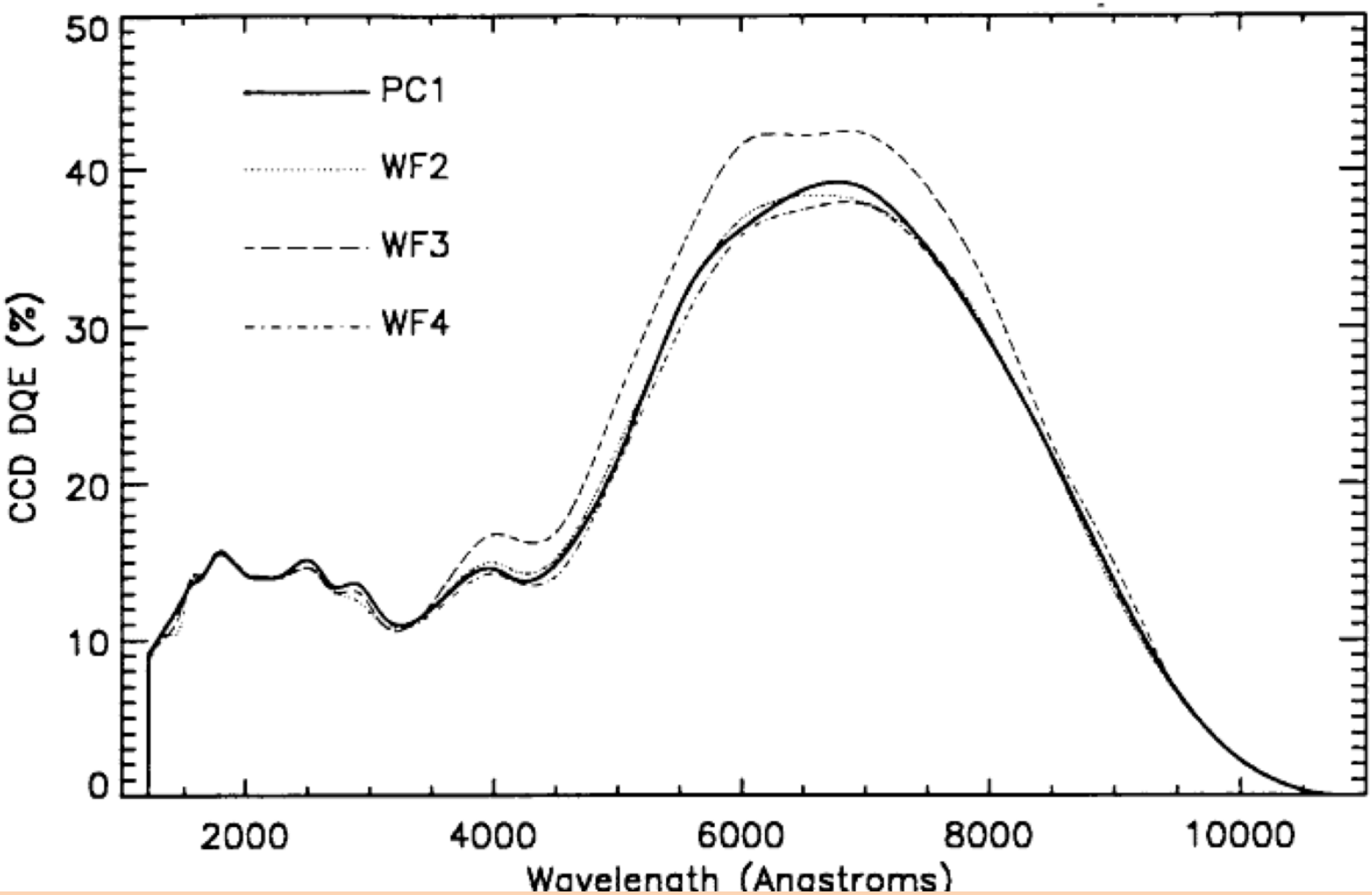
- WF/PC: 8 CCDs, each calibrated independently
- WFPC2: 4 CCDs, each calibrated independently
- ACS: 2 CCDS, treated as a single detector
  - Diced from same wafer, same QE
- WFC3/UVIS: 2 CCDs, initially calibrated as ACS
  - Different wafers, different runs, different QE
  - Since March 2016, each CCD calibrated independently
    - Flat fields improved by 2x in UV.
    - Accuracy improved by almost 3% (astrodrizzle subtlety)
- NICMOS: 3 HgCdTe detectors, individually calibrated
- WFC3/UVIS: 1 HgCdTe detector

ACS/WFC

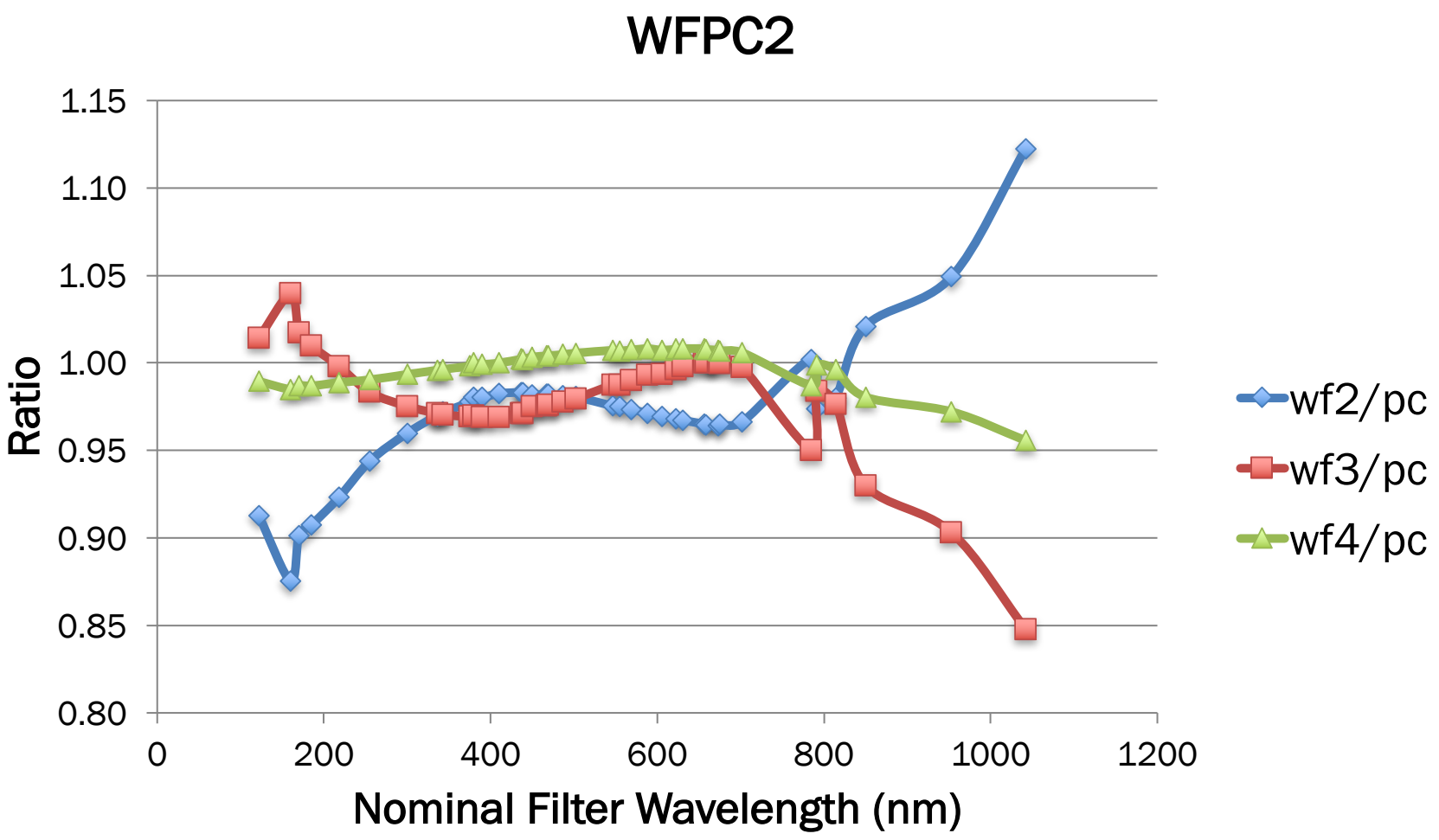

ACS WFC Detector QE
ACS WFC1
ACS WFC2
WFC1−WFC2
Quantum Efficiency
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
2000
4000
6000
8000
10000
Wavelength (Å)

WFPC2

Figure 4.2: Pre-flight DQE Measurements on WFPC2 CCDs



WFPC2 Response Ratios



Chip Dependent Photometry

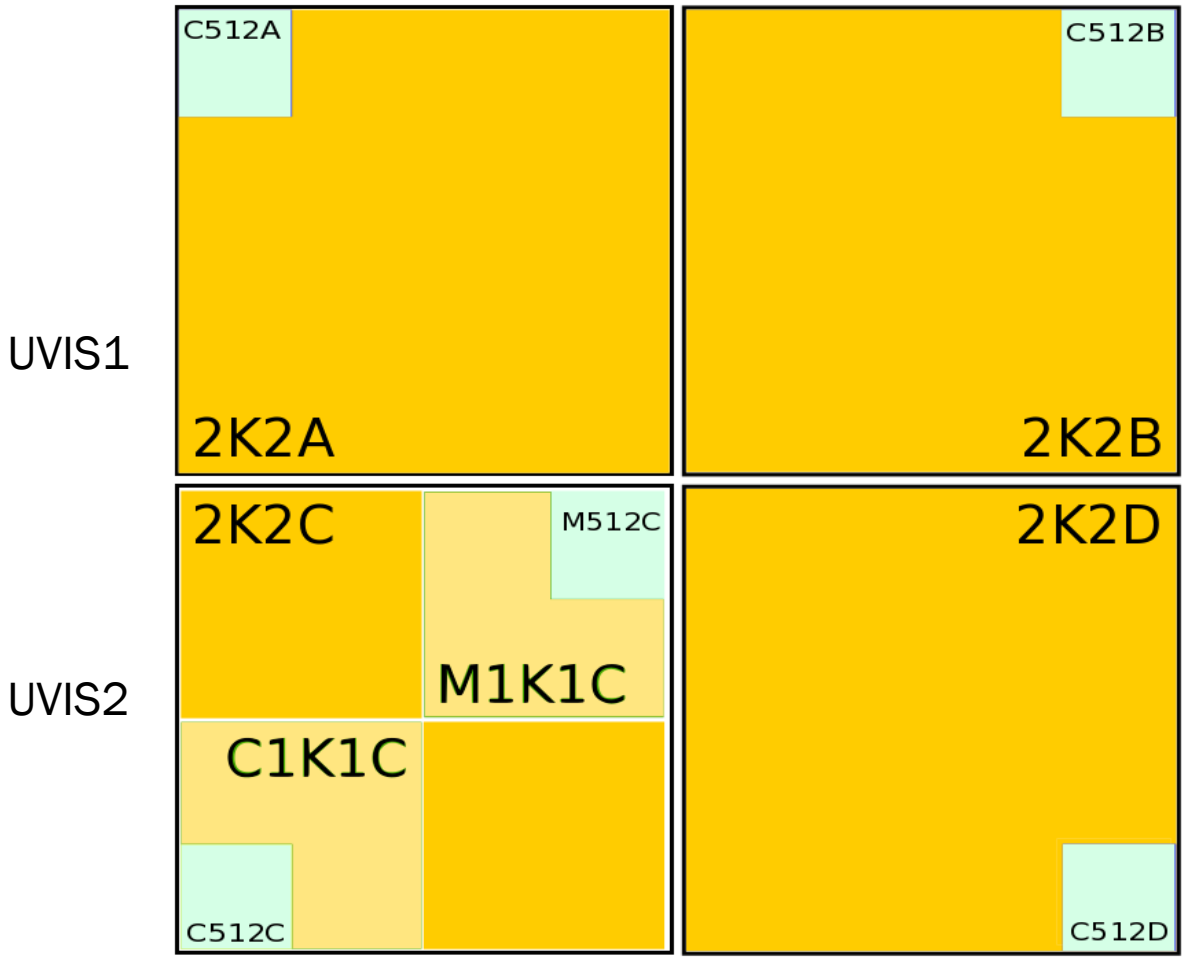
- Each CCD's photometry is determined independently
  - i.e think of WFC3/UVIS as 2 instruments
- Each WFC3 CCD/filter has its own flat
- Each flat is normalized to the median value of the CCD
- Each CCD/filter has its own inverse sensitivity value

  UVIS1+ filter ≠ UVIS2 + filter

Process

- All 2009 -2015 observations of standard stars, GD153, GD71, G191B2B
  - 4 corners, 1 middle subarrays.
- New flat fields made for each CCD, normalized to median
- Reprocess all data
- Perform aperture photometry, determine filter-based encircled energy fractions
- Compare measurements to SYNPHOT predictions
- Calculate inverse sensitivity for each CCD + filter, create new synphot tables, photometry reference files
- Update calwf3 (version 3.3) to handle chip dependent photometry
- Ingest into OPUS
- Reprocess all data

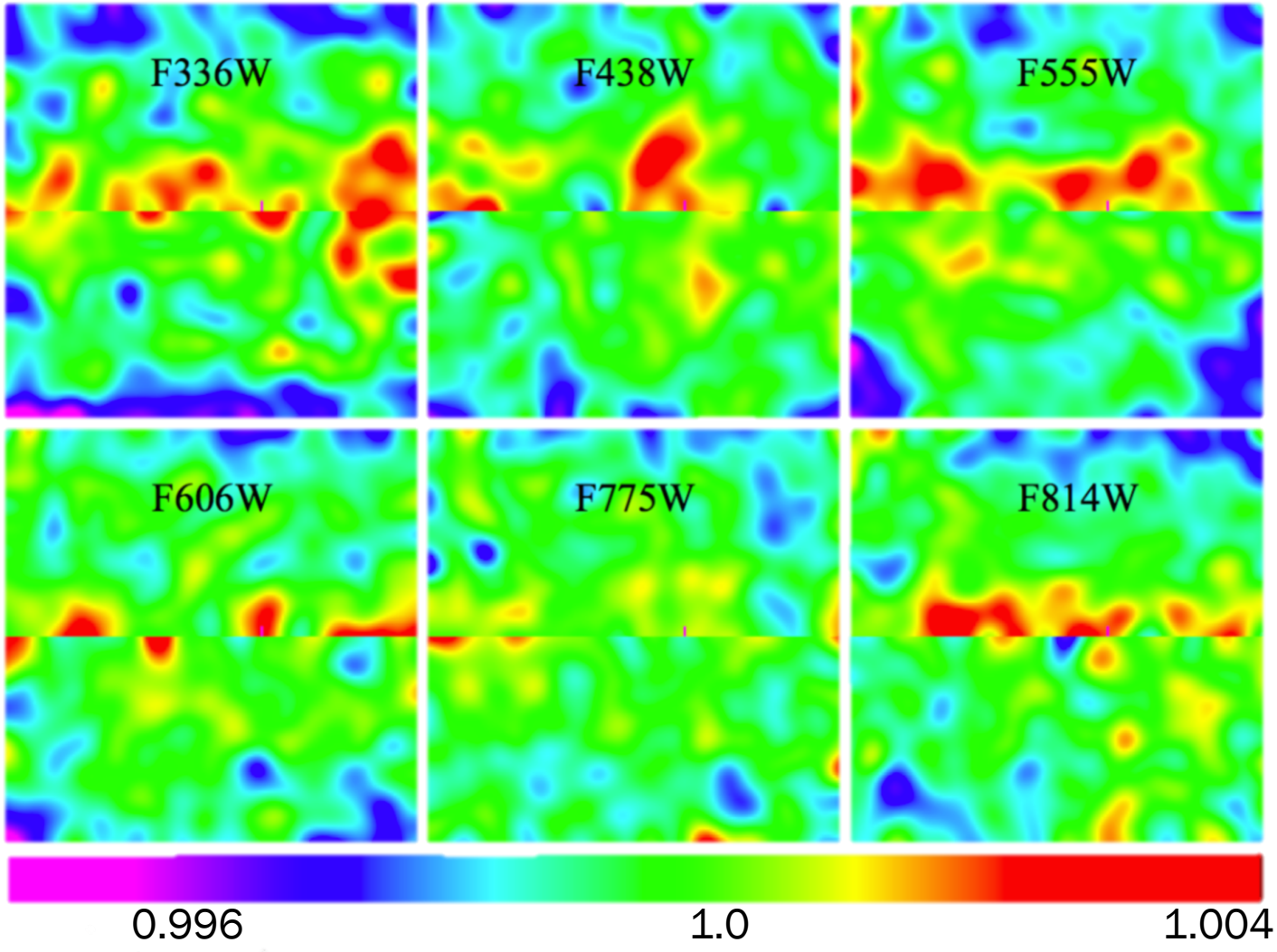
WFC3/UVIS Subarrays



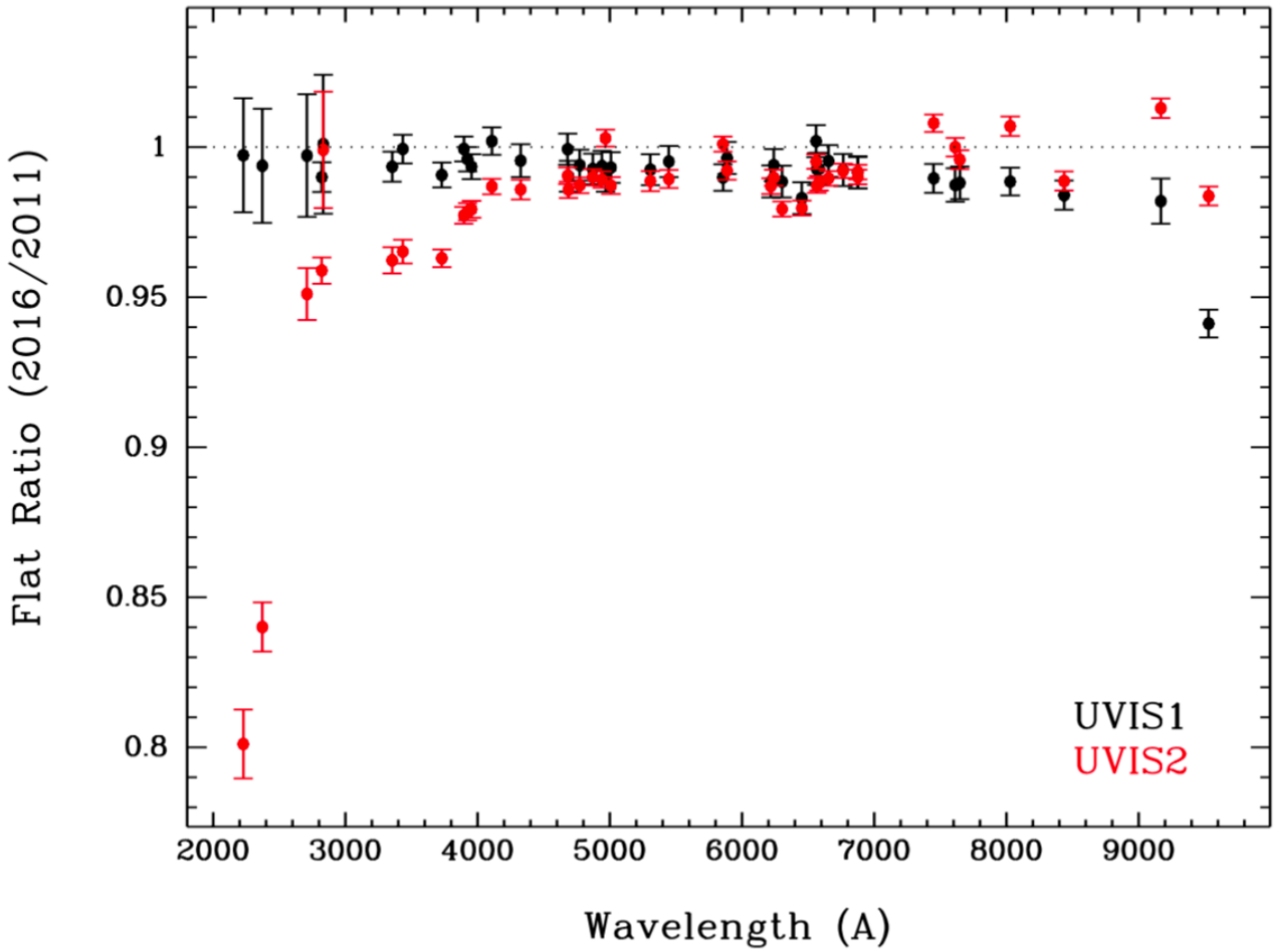
Flat Fields (imaging)

- **Pixel-to-pixel variation (Pflats)**
  - Acquired during thermal-vaccuum testing on the ground
    - Minimal set of images at 20K+ electrons per filter
    - Limited by schedule, typically
- **Low frequency spatial variation (Lflats)**
  - Created in orbit
    - star cluster(s) on different locations on the detector(s)
    - limited by spectral type, crowding, time
- **Sky flats**
  - Created from on orbit images
    - Better fidelity to the actual data
    - Requires hundreds of observations, more for bandpasses with low natural background

Flat field ratios: 2016/2011



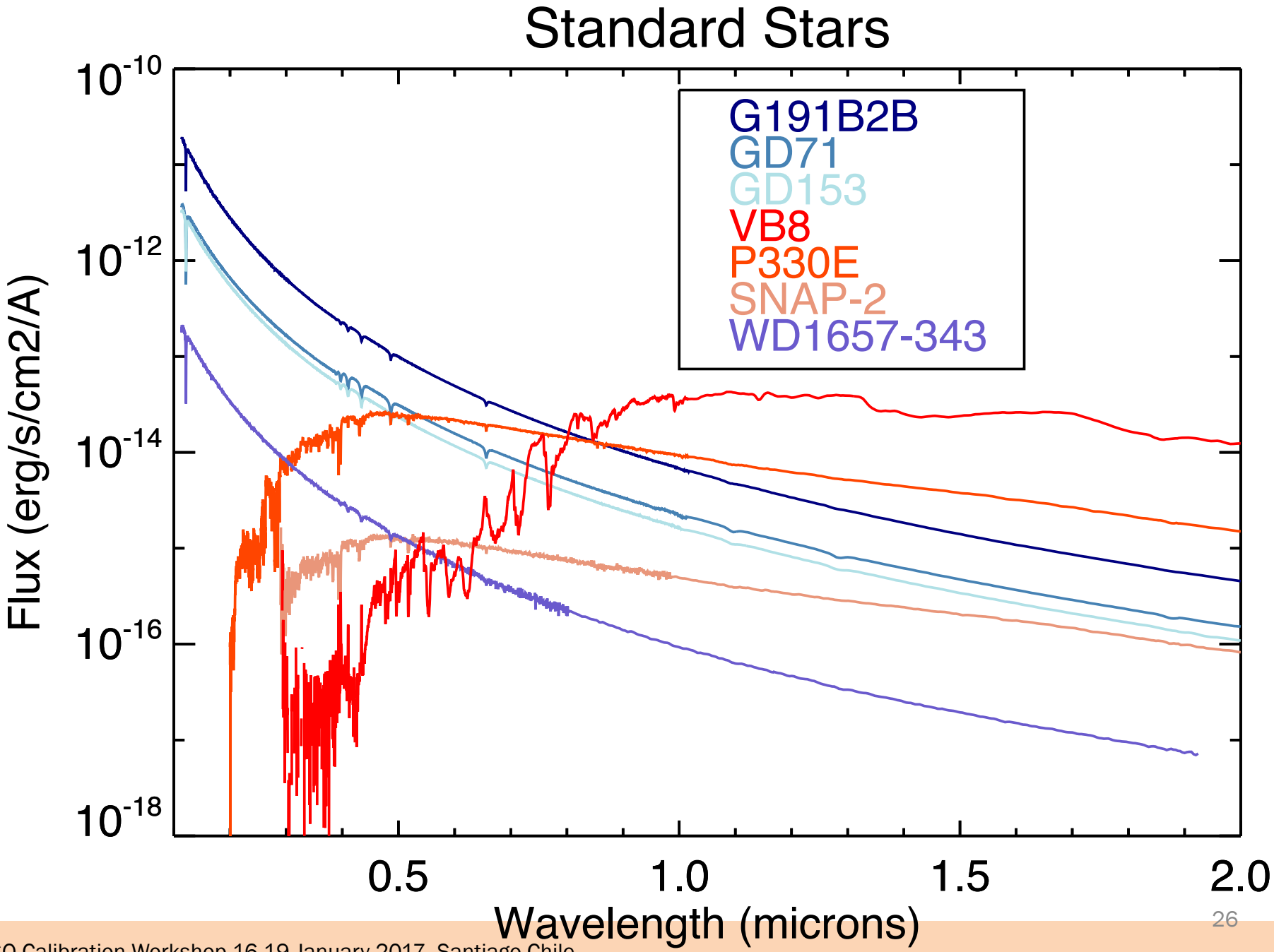
2016/2011 Flat ratios



After CTE Correction

Filter	Flat	Stddev	Stddev CTE-corr	P2P	P2P CTE-corr
F336W	2011	0.31%	0.28%	1.52 %	1.21 %
F336W	2016	0.37%	0.29%	1.73 %	1.22 %
F814W	2011	0.35%	0.29%	1.34 %	1.11 %
F814W	2016	0.42%	0.30%	1.74 %	1.15 %

	Name	Sp. Type	Vega mag B	V	R	I	J	H	
HST Primary Standards	G191B2B	DA.8	-	11.69	11.93	12.108	12.543	12.669	CALSPEC PEDIGREE: _stisnic_006
	GD71	DA1	12.783	13.032	13.169	13.337	13.728	13.901	
	GD153	DA1.2	13.17	13.346	13.8	13.3	14.012	14.2	
Secondary Standards	WD1657+343	DA1	16.12	16.16 (g)	16.69 (r)	17.06 (i)	>17	>17	
	WD1057+719	DA1.2	14.95	14.68	15.23	-	15.472	15.585	
	P330E	G2V	12.972	13.03	12.56	12.212	11.76	11.45	
	SNAP-2	G0-5	17.09	16.23	16.41	--	14.97	14.59	
	VB08	M7V	18.7	16.7	16.61	12.24	9.776	9.2	

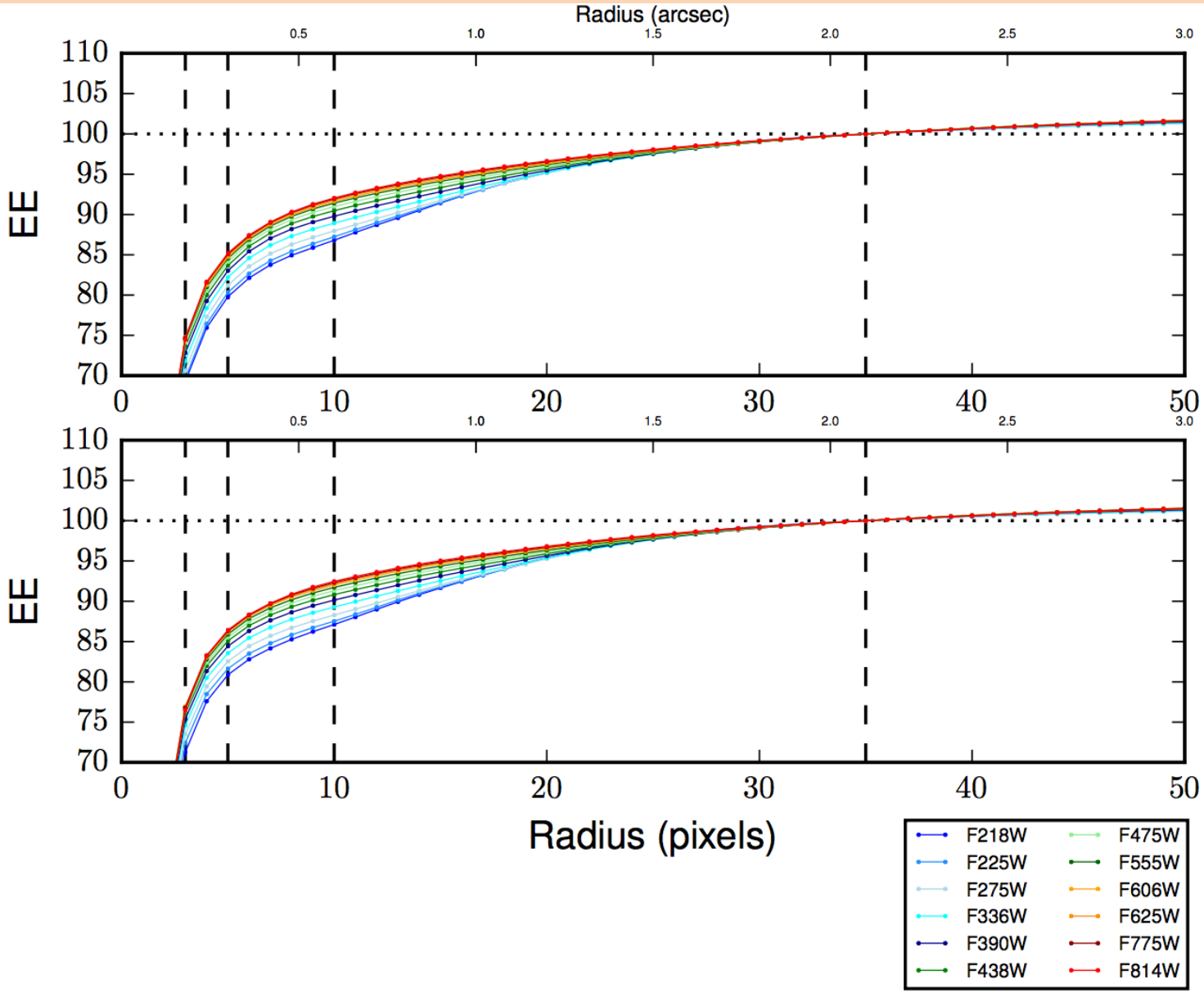

Standard Stars
G191B2B
GD71
GD153
VB8
P330E
SNAP-2
WD1657-343
Flux (erg/s/cm2/A)
10-10
10-12
10-14
10-16
10-18
0.5
1.0
1.5
2.0
Wavelength (microns)

Spatial Variation: repeatability

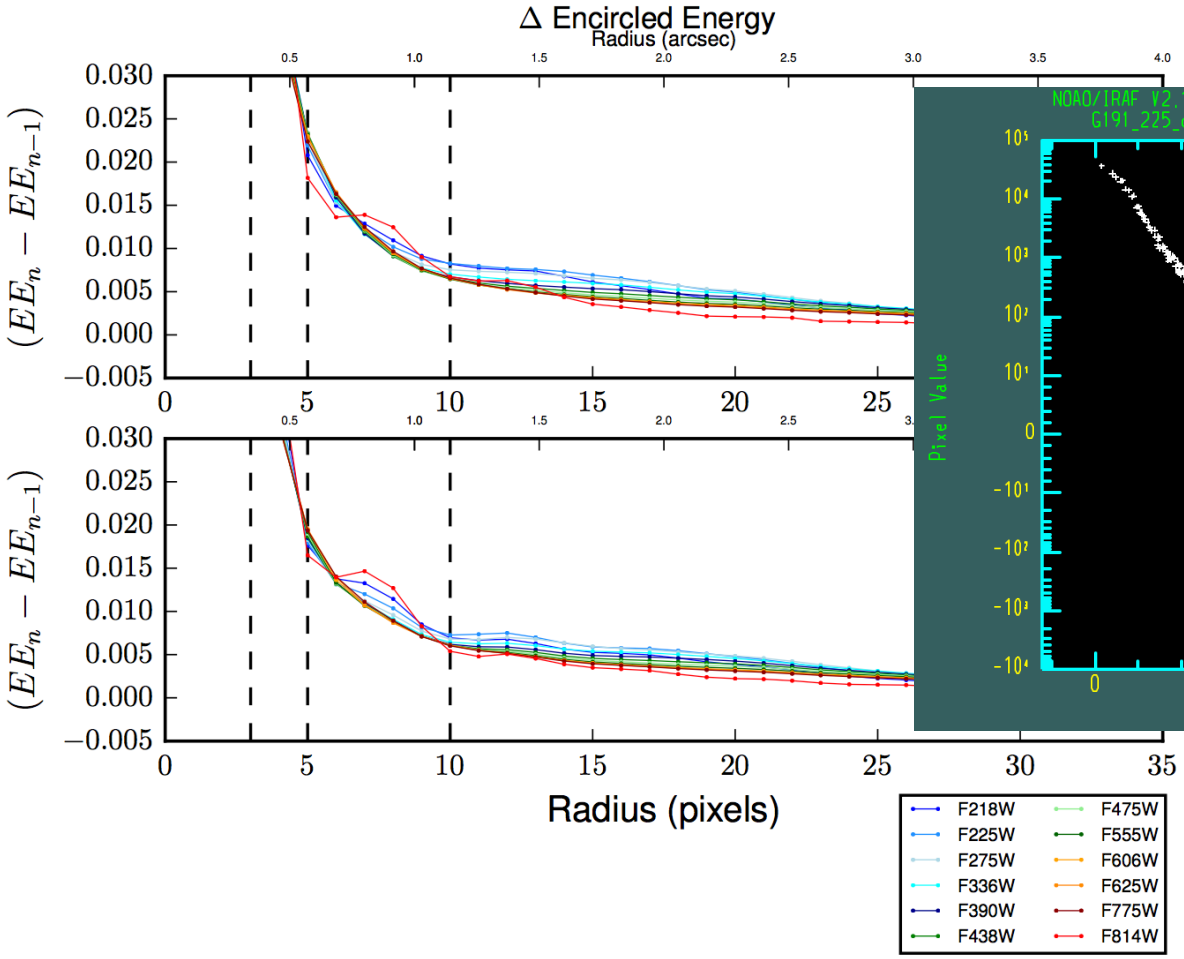
Filter	Number of Steps	Poisson Error	Stddev (2011)	Stddev (2016)	P2P (2011)	P2P (2016)
F218W	44	0.2%	1.5 %	0.7 %	6.7 %	3.0 %
F225W	44	0.2%	1.3 %	0.4 %	4.5 %	1.8 %
F275W	41*	0.2%	0.8 %*	0.6 %	3.3 %*	2.7 %
F280N	44	0.2%	1.8 %	0.5 %	6.6 %	2.4 %
F336W	46	0.4%	0.3 %	0.4 %	1.5 %	1.7 %
F438W	50	0.2%	0.5 %	0.5 %	2.0 %	2.3 %
F606W	20	0.3%	0.7 %	0.7 %	2.7 %	2.7 %
F814W	50	0.3%	0.4 %	0.4 %	1.3 %	1.7 %

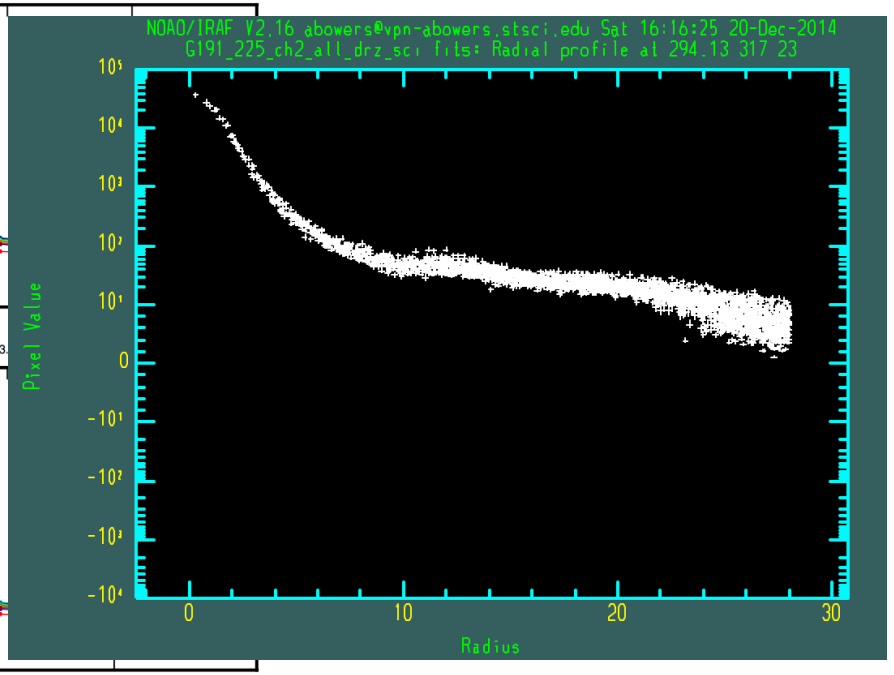
J. Mack, A. Bowers

Filter Based EE curves



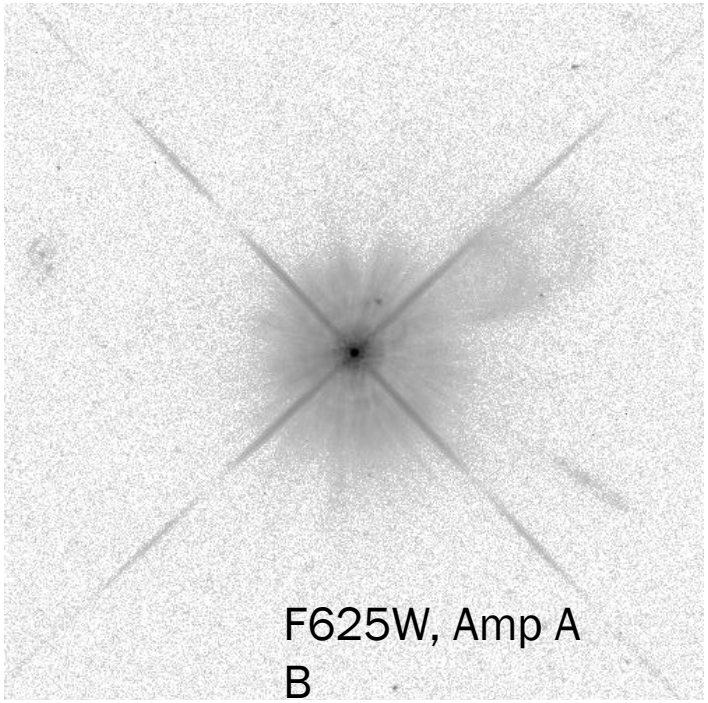
Delta EE curves



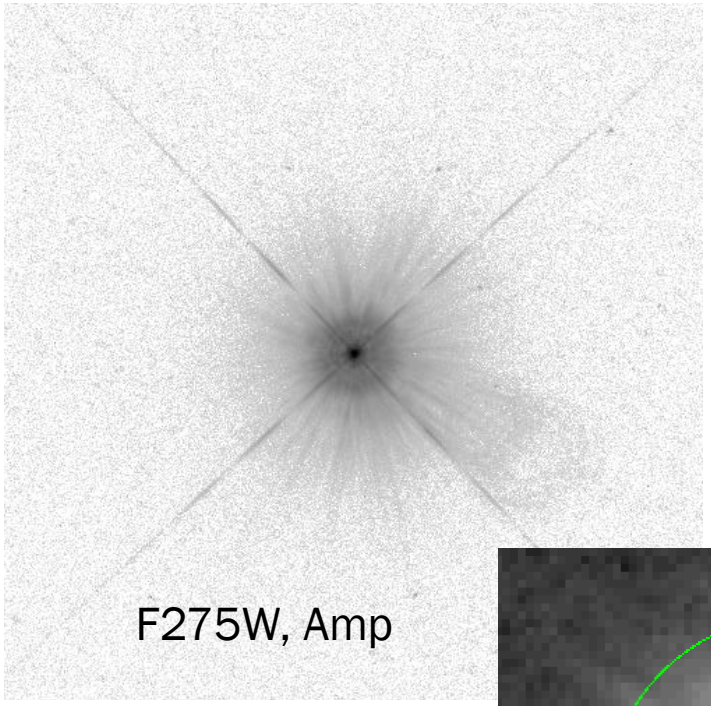


F225W, Chip 2 by A. Bowers (2016)

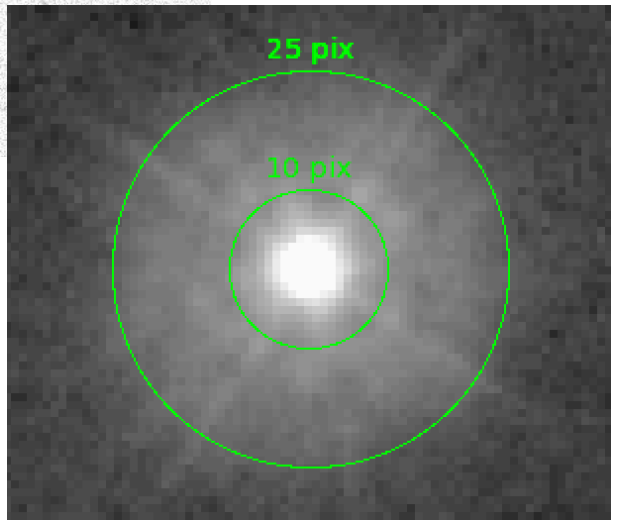
UVIS PSF



F625W, Amp A
B



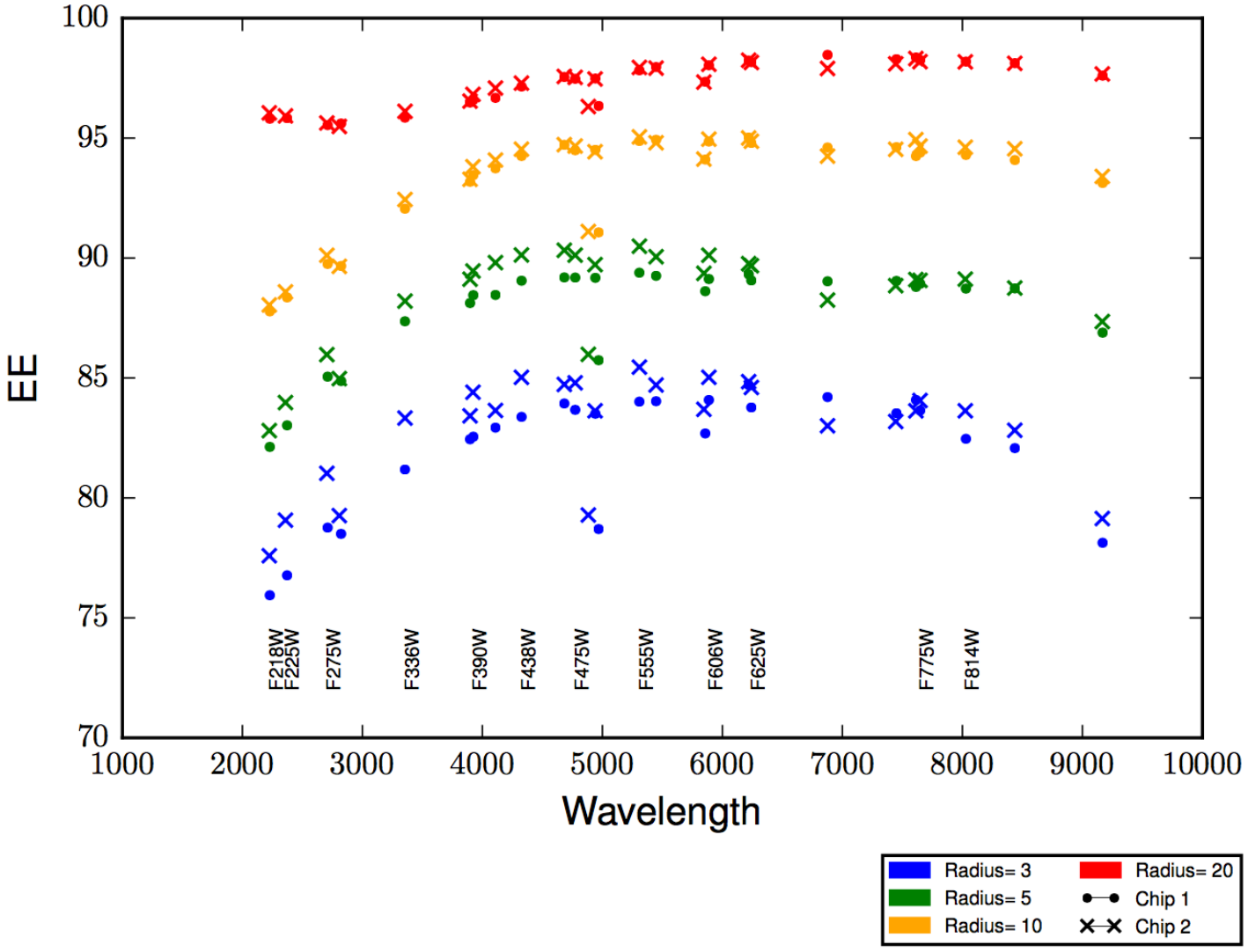
F275W, Amp



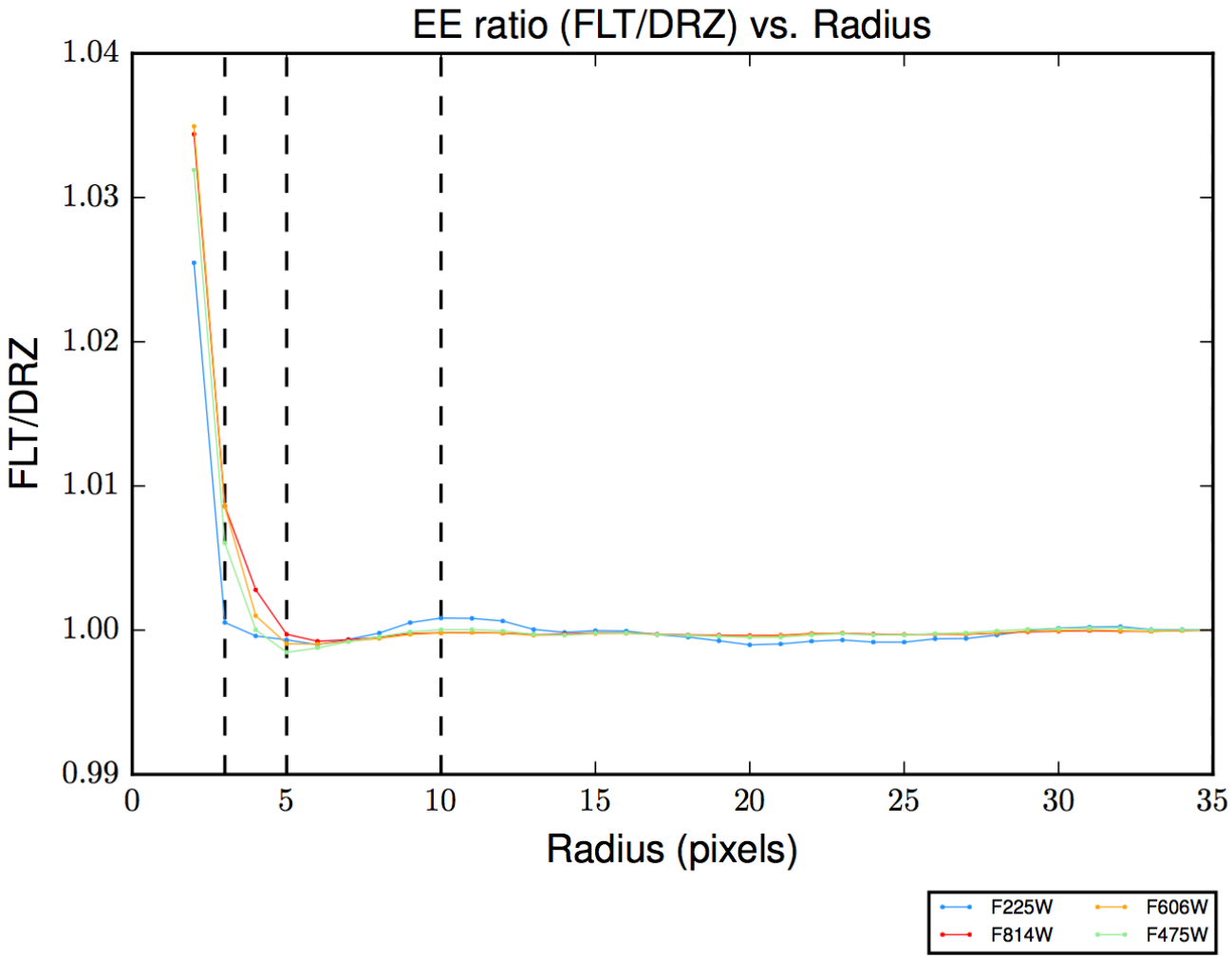
GRW +70 5824

Hartig 2009, A Bowers, 2016

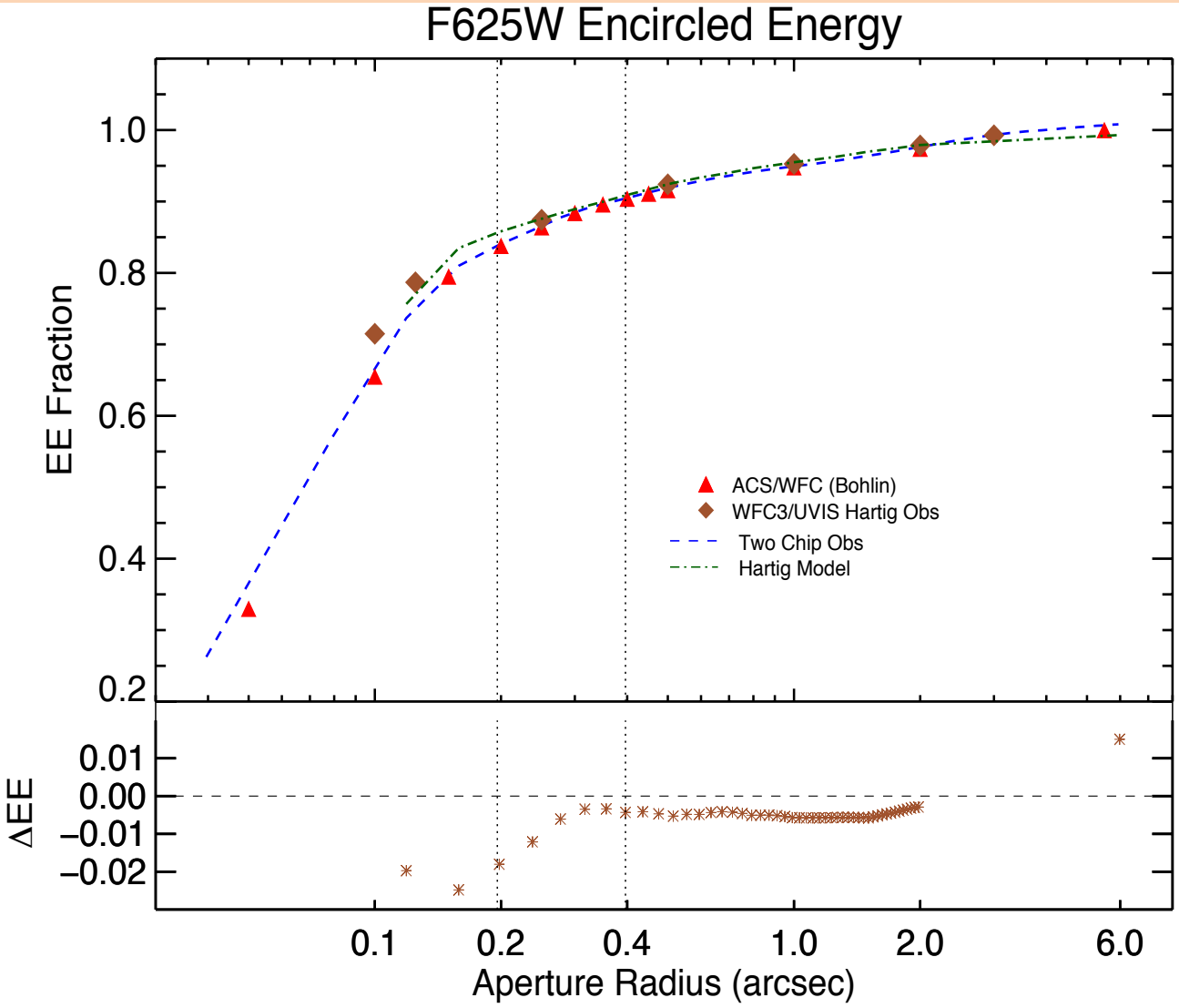
EE vs. Filter


EE
Wavelength
100
95
90
85
80
75
70
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
F218W
F225W
F275W
F336W
F390W
F438W
F475W
F555W
F606W
F625W
F775W
F814W
Radius= 3
Radius= 5
Radius= 10
Radius= 20
Chip 1
Chip 2

FLT vs. DRZ EE


EE ratio (FLT/DRZ) vs. Radius
FLT/DRZ
1.04
1.03
1.02
1.01
1.00
0.99
0
5
10
15
20
25
30
35
Radius (pixels)
F225W
F606W
F814W
F475W

ACS-WFC3 EE comparison



Inverse Sensitivity

Per Bohlin 2014

The Photon weighted mean flux in a bandpass is

$$\langle F \rangle = \int F_\lambda \lambda R d\lambda \,/\, \int \lambda R \, d\lambda = S \times N_e$$

F in ergs s^{-1} cm^{-2} $Å^{-1}$, N_e in e-/s,

If the instrument throughput parameters and the source flux density is known, the count rate can be predicted from:

$$\mathrm{N}_e = \frac{A}{hc} \int F_\lambda \lambda R d\lambda$$

And

$$S = \frac{\langle F \rangle}{N_e} = \frac{hc}{A \int \lambda R \, d\lambda}$$

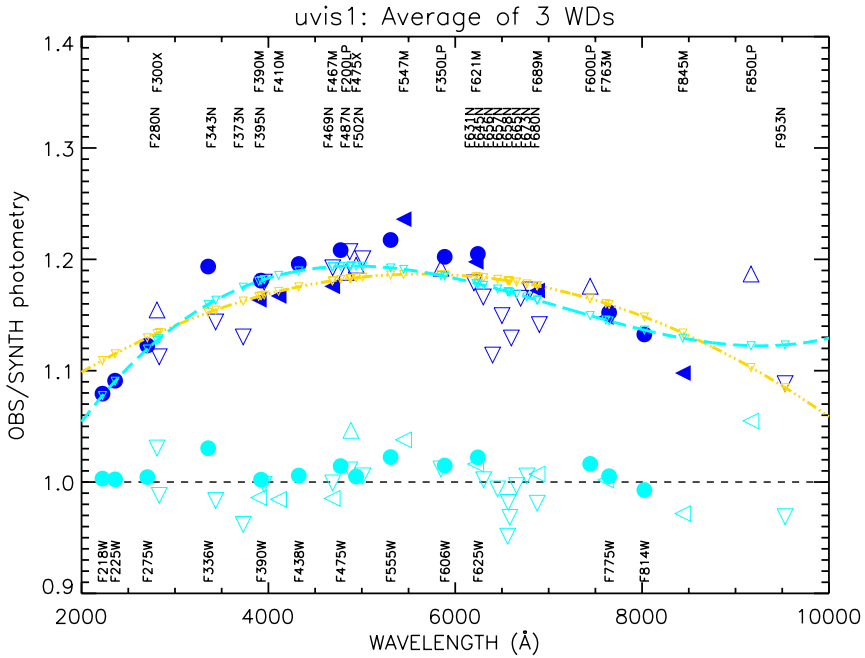
S= ergs cm^{-2} $Å^{-1}$ e^{-1}

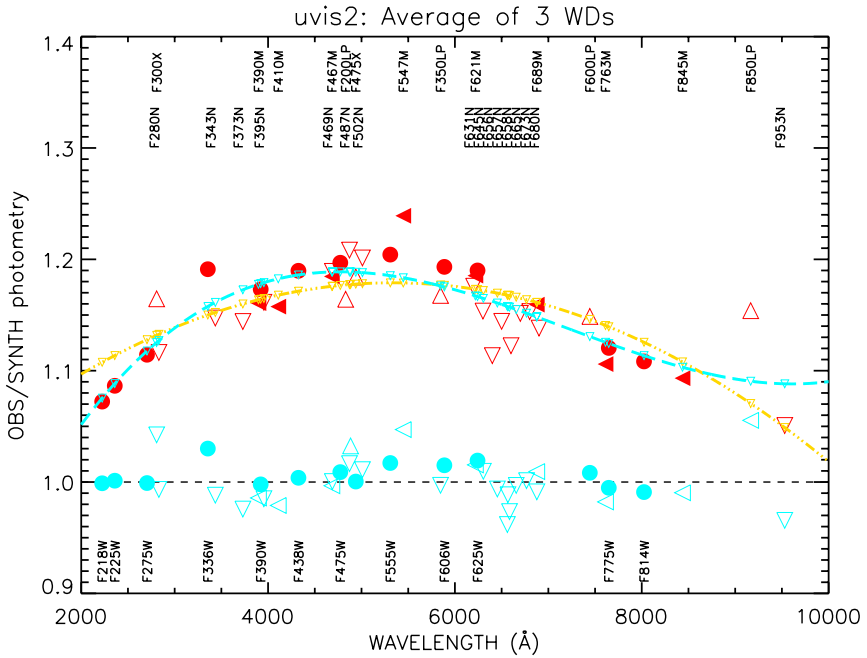
$$photflam = flam \,/\, N_e$$

Synthetic Photometry

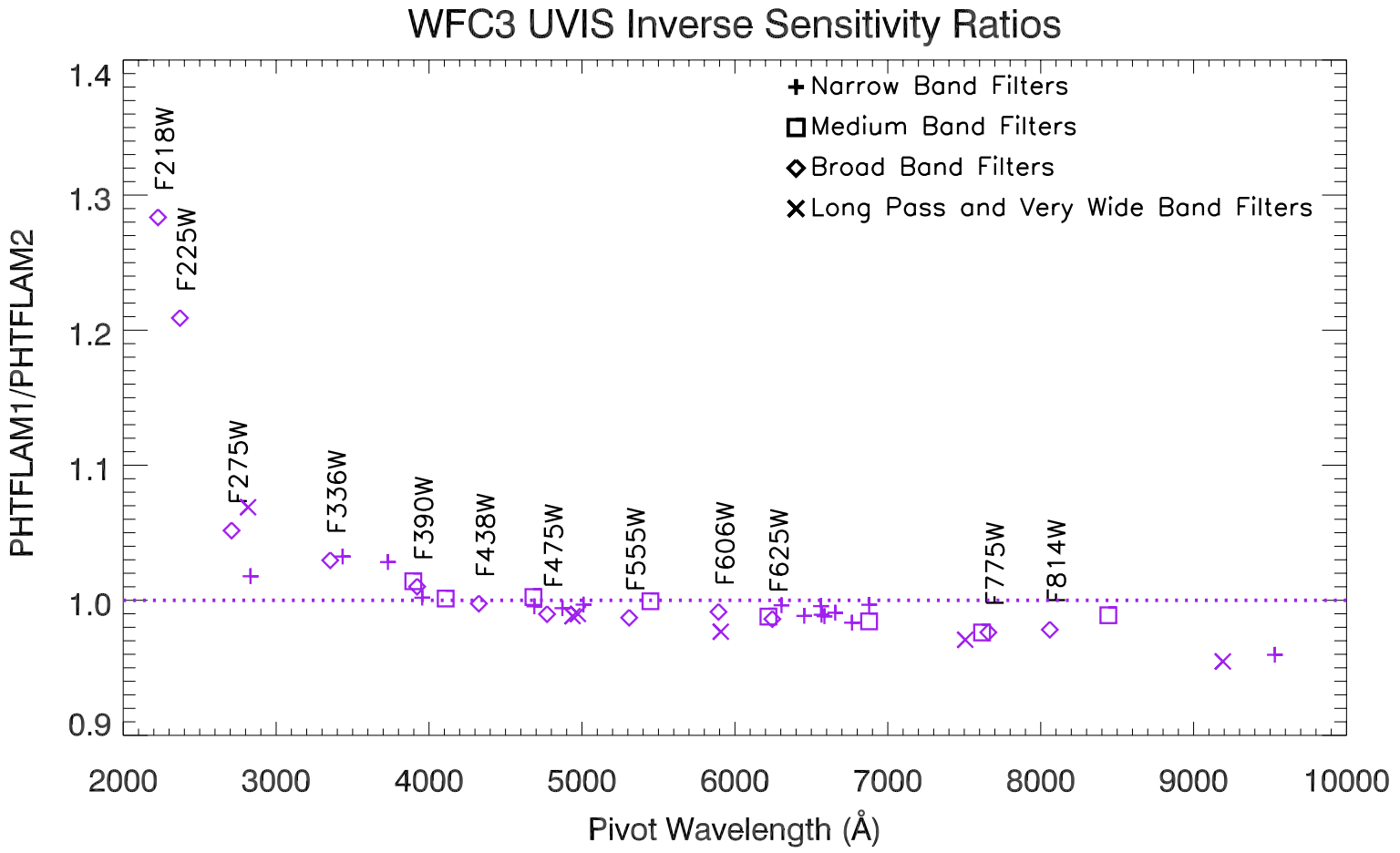
- 'fixed' Instrument parameters:
  - optical telescope assembly (OTA)
  - pick off mirror reflectivity (POM)
  - Mirror 1 & Mirror 2 (mir1, mir2)
  - Outer and Inner dewar window (owin, iwin)
  - Filter transmission
  - Detector quantum efficiency
- 'inflight' parameters
  - Detector gain
  - Encircled energy
  - Flat fields
- Spectrum
  - Model stellar atmosphere for the primary standard stars: GD153, GD71, G191B2B

Observed to Synthetic Photometry

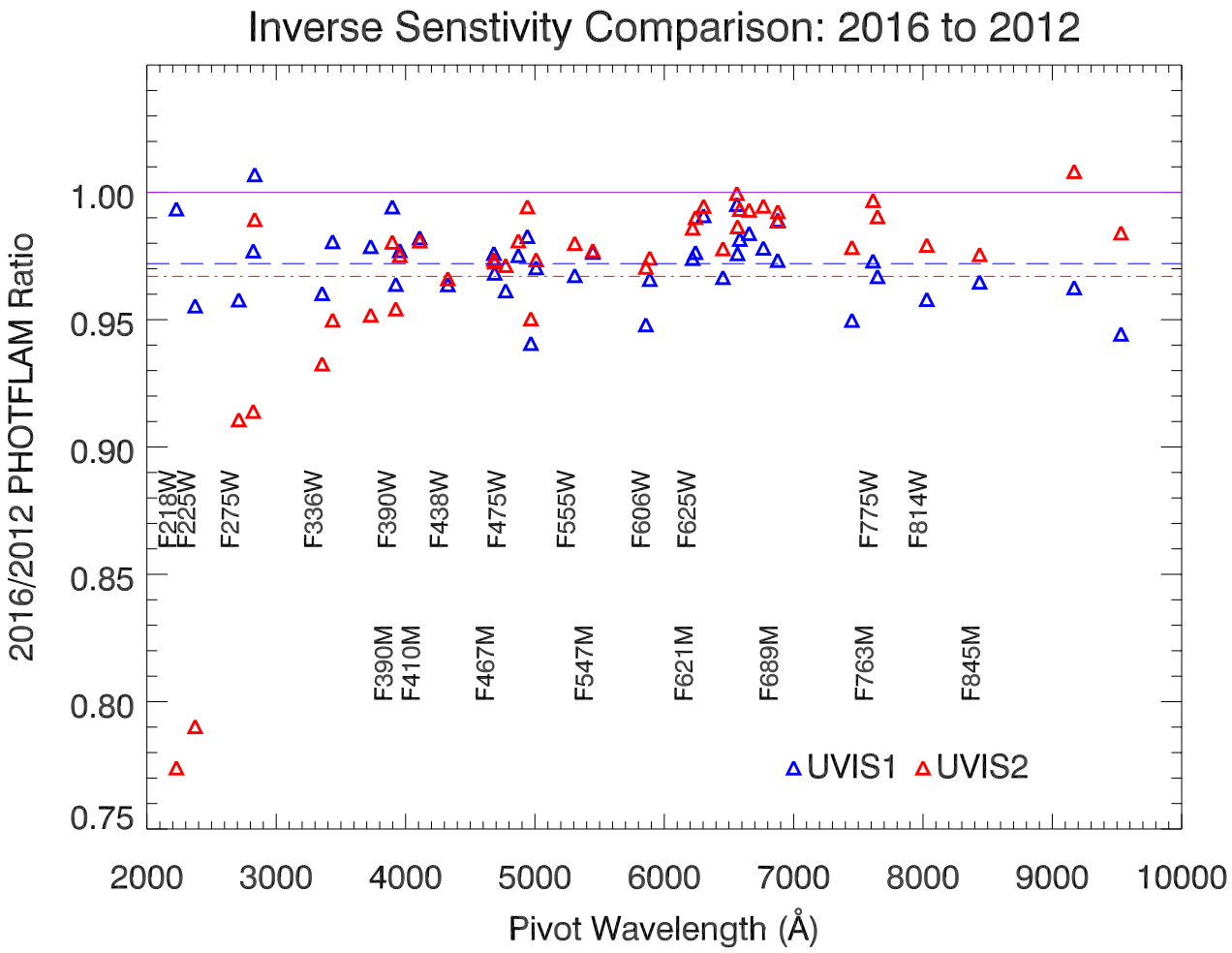




UVIS1/UVIS2 Inverse Sensitivity Ratios



2016 to 2012 Comparison



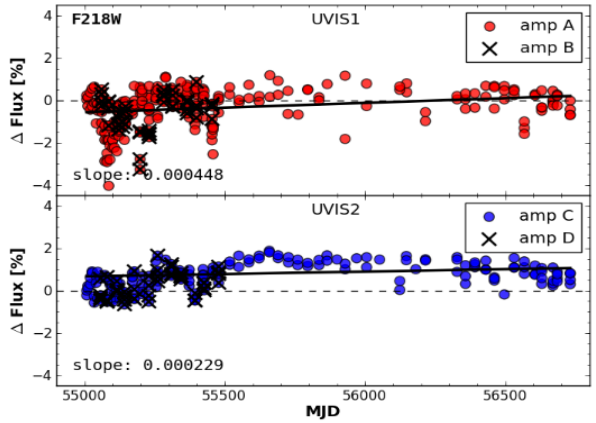
CALWF3

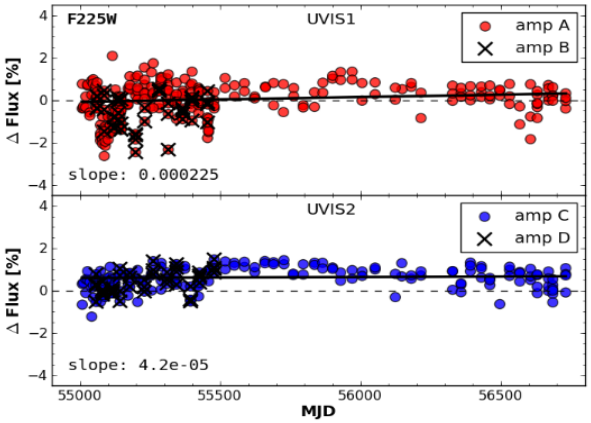
- **Header Keywords**
  - PHOTFLAM: inverse sensitivity for UVIS 1
  - PHTFLAM1: inverse sensitivity for UVIS1
  - PHTFLAM2: inverse sensitivity for UVIS2
  - PHTRATIO: PHTFLAM1/PHTFLAM2
- **CAL Switches**
  - PHOTCORR
    - = PERFORM then PHTRATIO is calculated and keywords are populated in the header
  - FLUXCORR
    - =PERFORM then chip2 is scaled to chip1

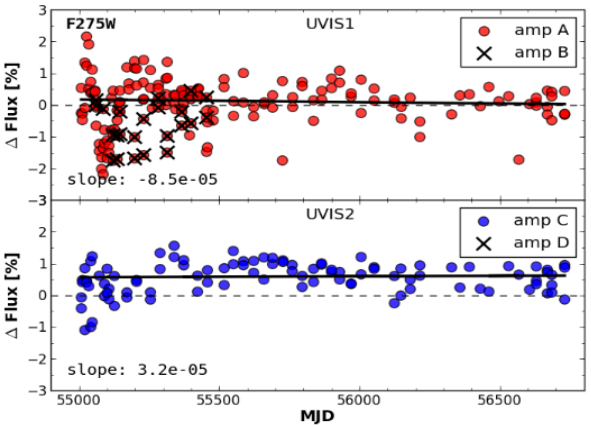
Photometry Lookup Table
IMPHTTAB

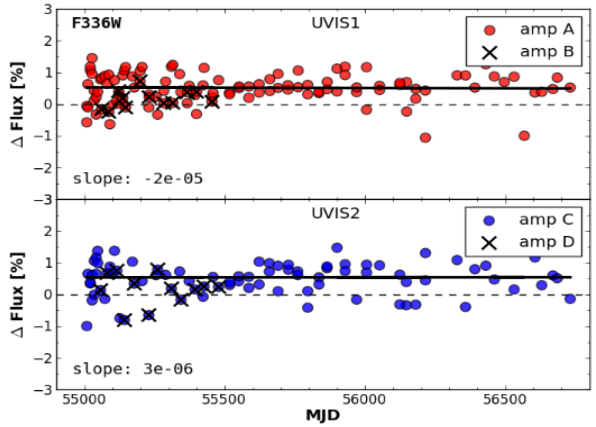
	EXT 1	EXT 2	EXT 3	EXT 4	EXT 5	FORMAT
Col 1	OBSMODE	OBSMODE	OBSMODE	OBSMODE	OBSMODE	CH*40
Col 2	DATACOL	DATACOL	DATACOL	DATACOL	DATACOL	CH*12
Col 3	PHOTFLAM	PHOTPLAM	PHOTBW	PHTFLAM1	PHTFLAM2	D (25.16g)
Col 4	PEDIGREE	PEDIGREE	PEDIGREE	PEDIGREE	PEDIGREE	CH*30
Col 5	DESCRIP	DESCRIP	DESCRIP	DESCRIP	DESCRIP	CH*110

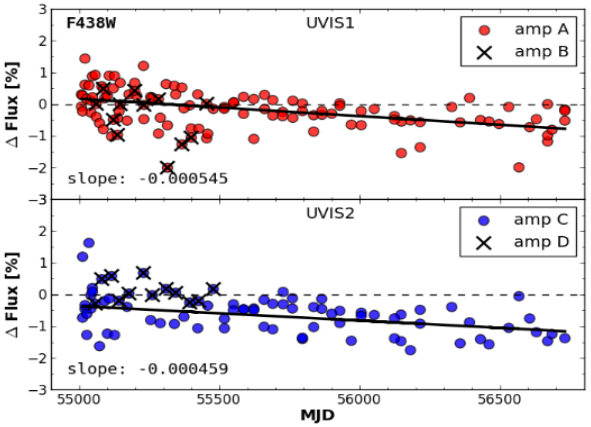
row	OBSMODE	DATACOL	PHTFLAM2	PEDIGREE	DESCRIP
1	wfc3,uvis2,f336w	PHTFLAM2	1.27E-18	INFLIGHT	Chip Dependent
2	wfc3,uvis2,f275w	PHTFLAM2	3.14E-18	INFLIGHT	Chip Dependent

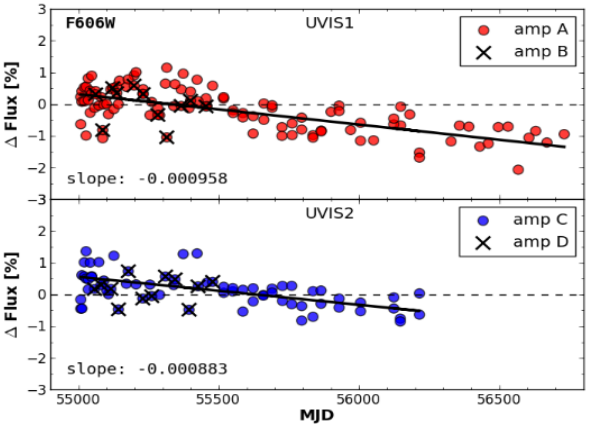


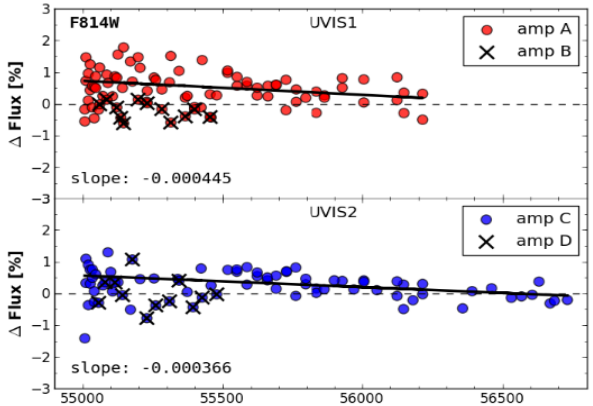












Gosmeyer+ 2015

Results

- Flat fields improved by up to 2-3 x (0.6%)
- Measured EE spatial variation is ~ 0.1% at r > 5 pixels
- Spatial repeatability is ~0.3%
- Inverse sensitivities are more accurate by 3%

Accuracy and Precision

Systematic Error Estimates:

- **Uncertainty in Vega Flux: ~0.7% @ 5557Å**
- **Uncertainty in models : <1% in UVIS, ~ 2% in NIR**

Statistical Error Estimates (Measurement Precision):

  - **Poisson: 0.2%**
  - **Flat fields: ~0.4%-0.6% (filter/detector dependent)**
  - **Repeatability: 0.2-0.5% (detector dependent)**
  - **Other: = 0.5% - 1%**
    - **Processing noise (bias & dark subtraction, flatfielding), gain, readnoise, CTE(CCDS), persistence (HgCdTe), count rate and count non-linearities**

- **WFC3/UVIS: 1.3% (stat)+ 1.22%(syst)**
- **WFC3/IR: ~1.6% (stat) + 2.1%(syst)**

A

THE END

HST Standard Stars

- **Normalized to Vega flux at 5557Å**
  - **$3.44 \times 10^{?9}$ erg cm^{-2} s^{-1} Å (Bohlin, 2014 AJ, 147, 127)**
  - **Kurucz Vega Model (2013 kupdated)**
- **Originally LTE WD models (Finley, Hubeny)**
- **Now use NLTE WD models (Rauch)**