Calibration of the Hubble Space Telescope's Wide Field Camera 3 (WFC3): a case study

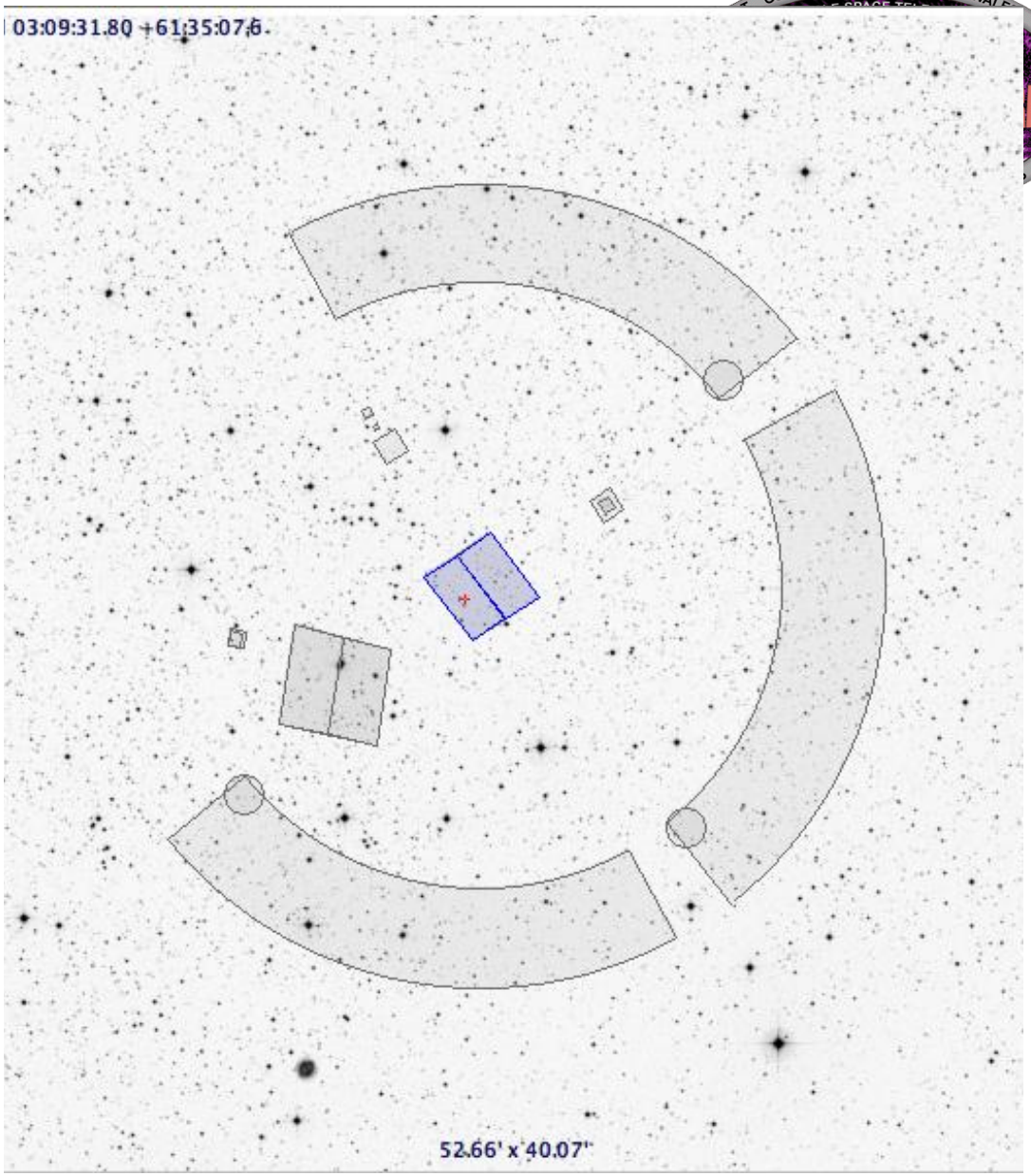
Susana Deustua
Space Telescope Science Institute
Baltimore, MD

Current WFC3 Team

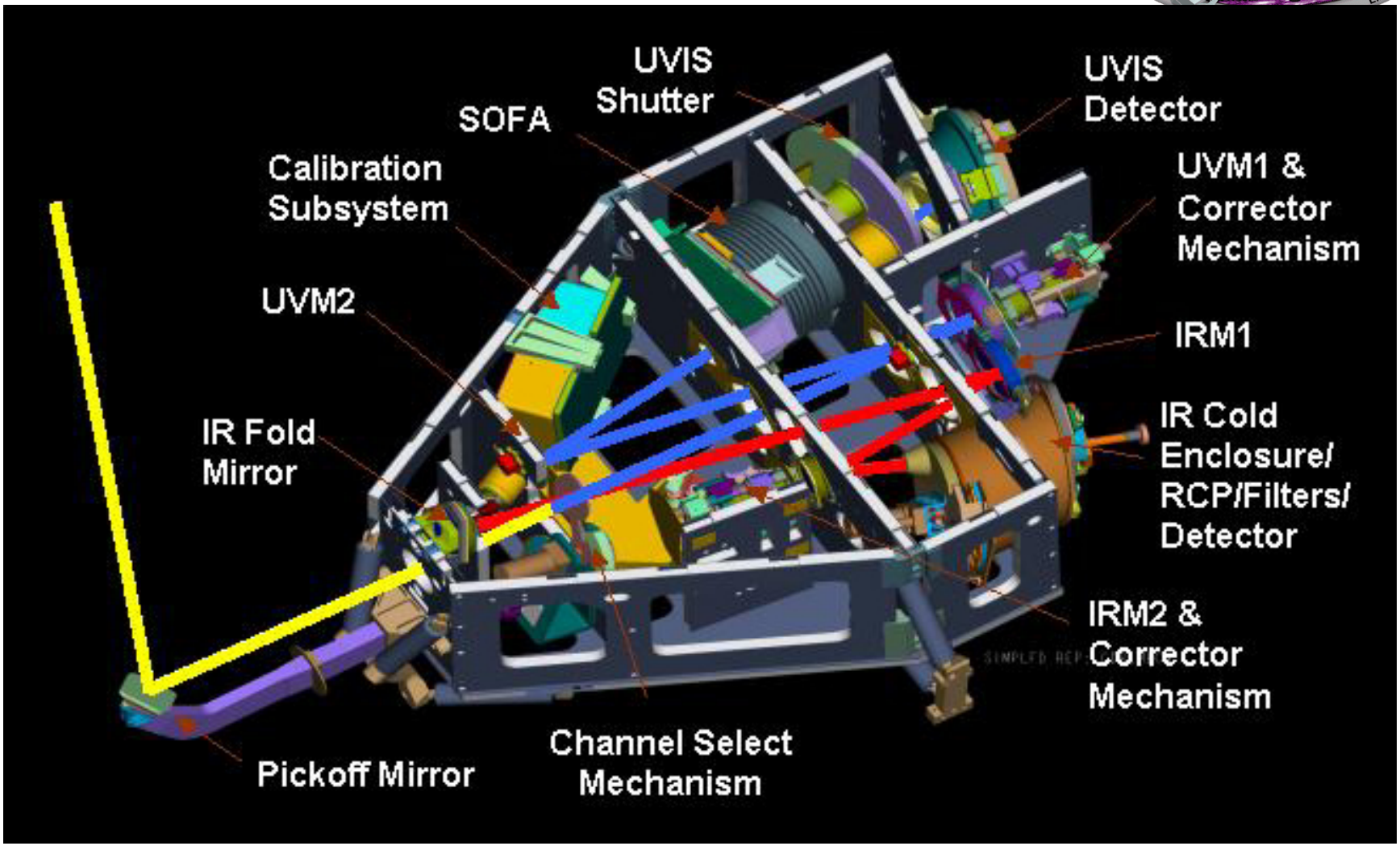
- John MacKenty (Team Lead)
- Peter McCullough
- Kai Noeske
- Cheryl Pavlovsky
- Larry Petro
- Nor Pirzkal
- Adam Riess
- Elena Sabbi
- Megan Sosey
- Alex Viana
- Tom Wheeler

- Sylvia Baggett
- John Biretta
- Tiffany Borders Davis
- Matthew Bourque
- Thomas Dahlen
- Linda Dressel
- Susana Deustua
- Michael Dulude
- Bryan Hilbert
- Vera Kozhurina-Platais
- Janice Lee
- Knox Long
- Jennifer Mack

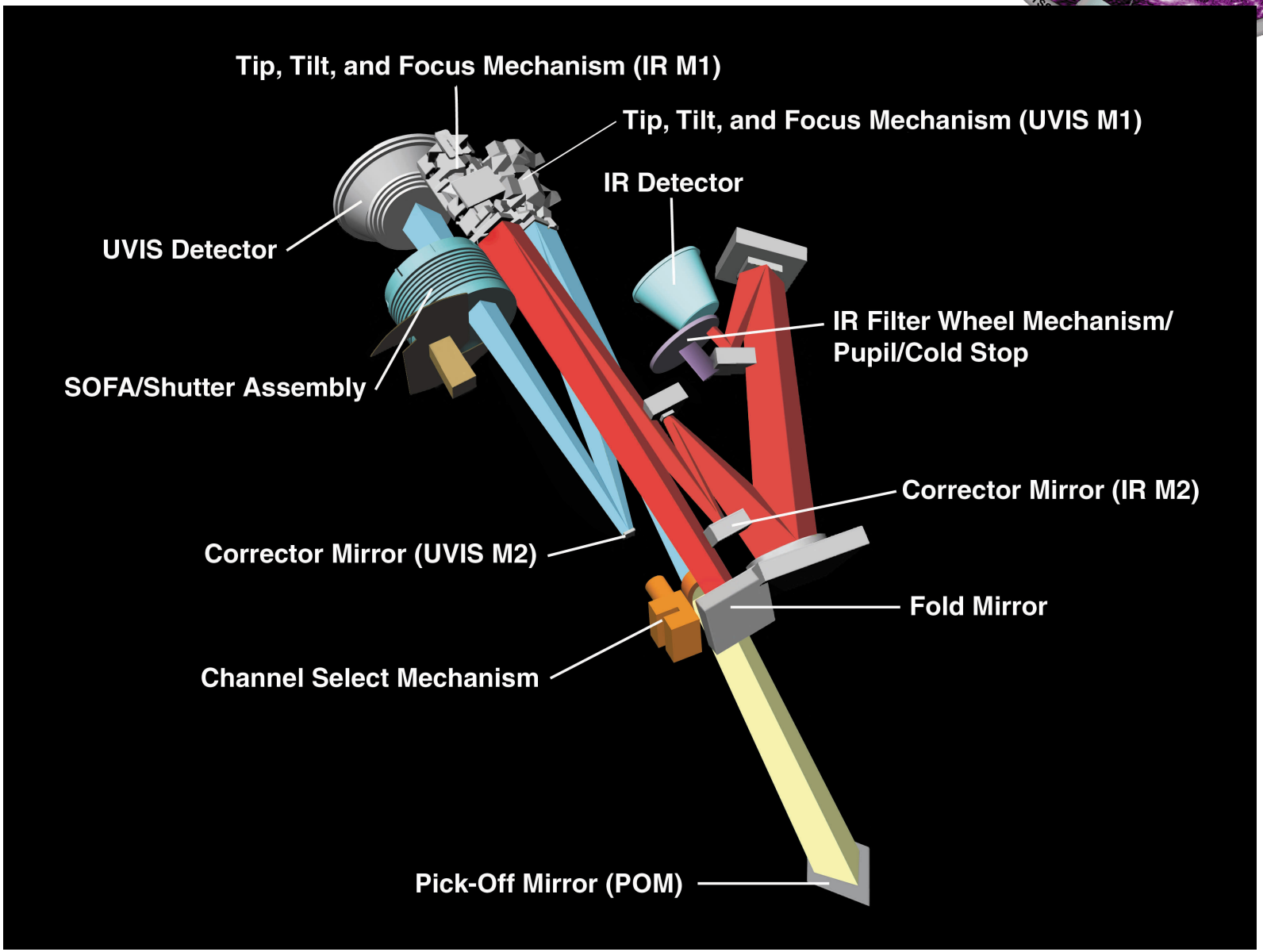
WFC3 focal plane



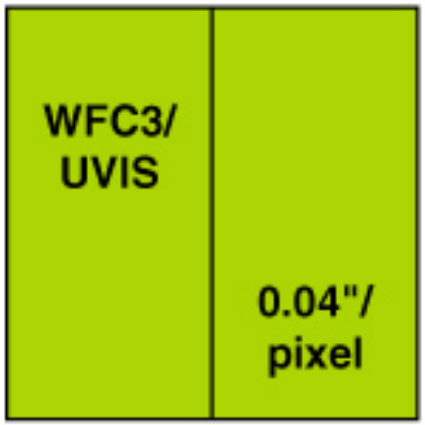
WFC3

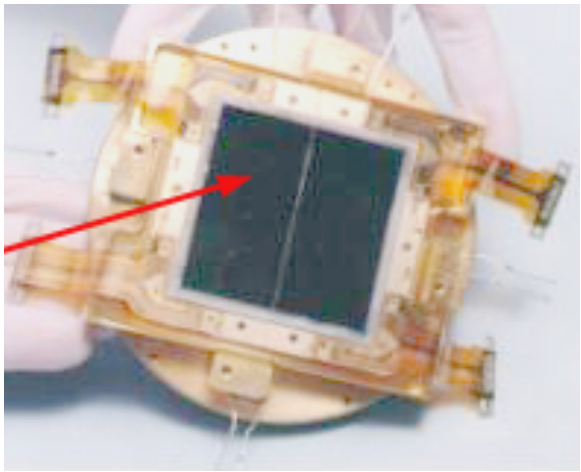

UVIS Shutter
SOFA
Calibration Subsystem
UVM2
IR Fold Mirror
Pickoff Mirror
Channel Select Mechanism
UVIS Detector
UVM1 & Corrector Mechanism
IRM1
IR Cold Enclosure/ RCP/Filters/ Detector
IRM2 & Corrector Mechanism

Just the beam

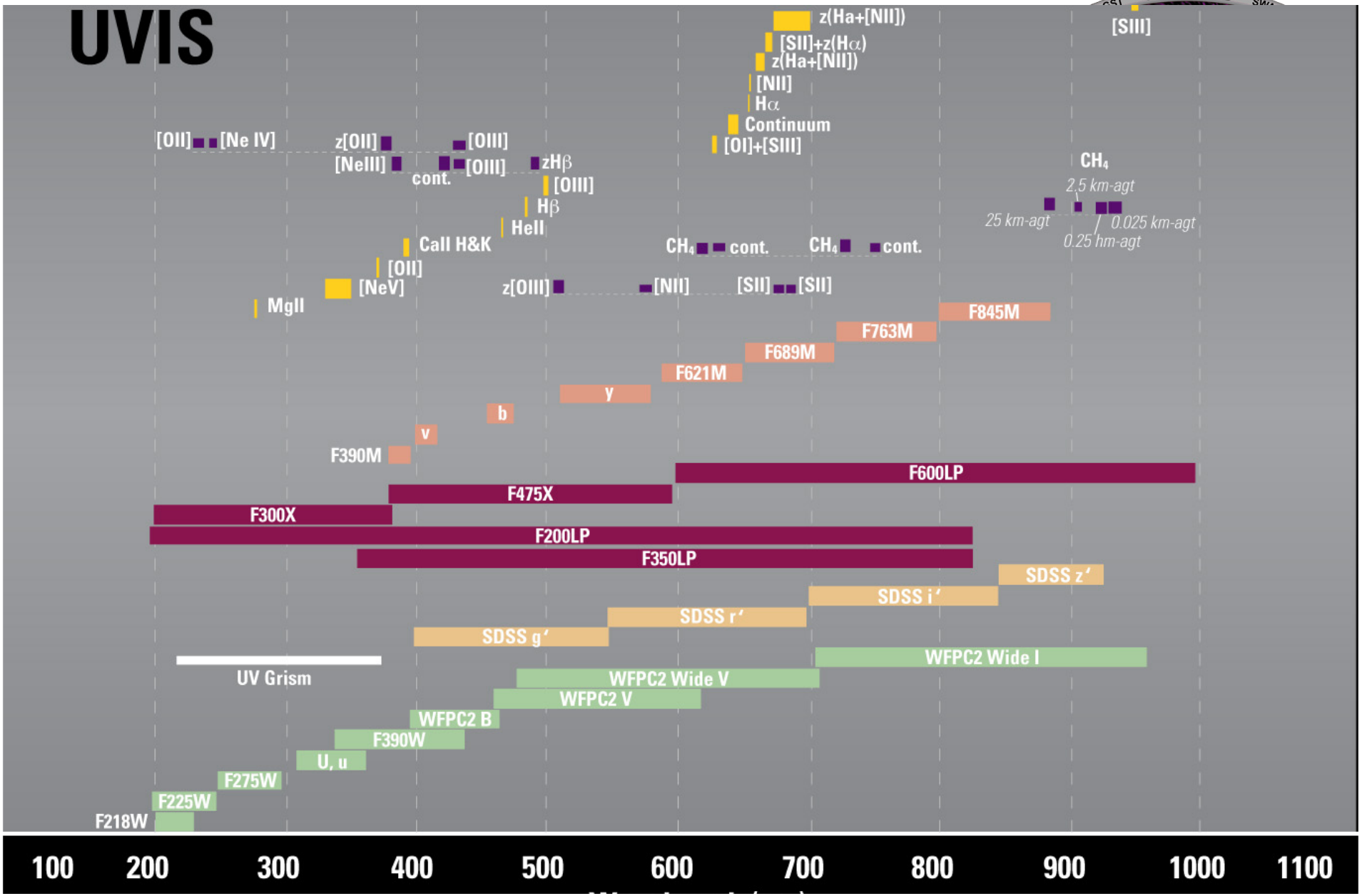


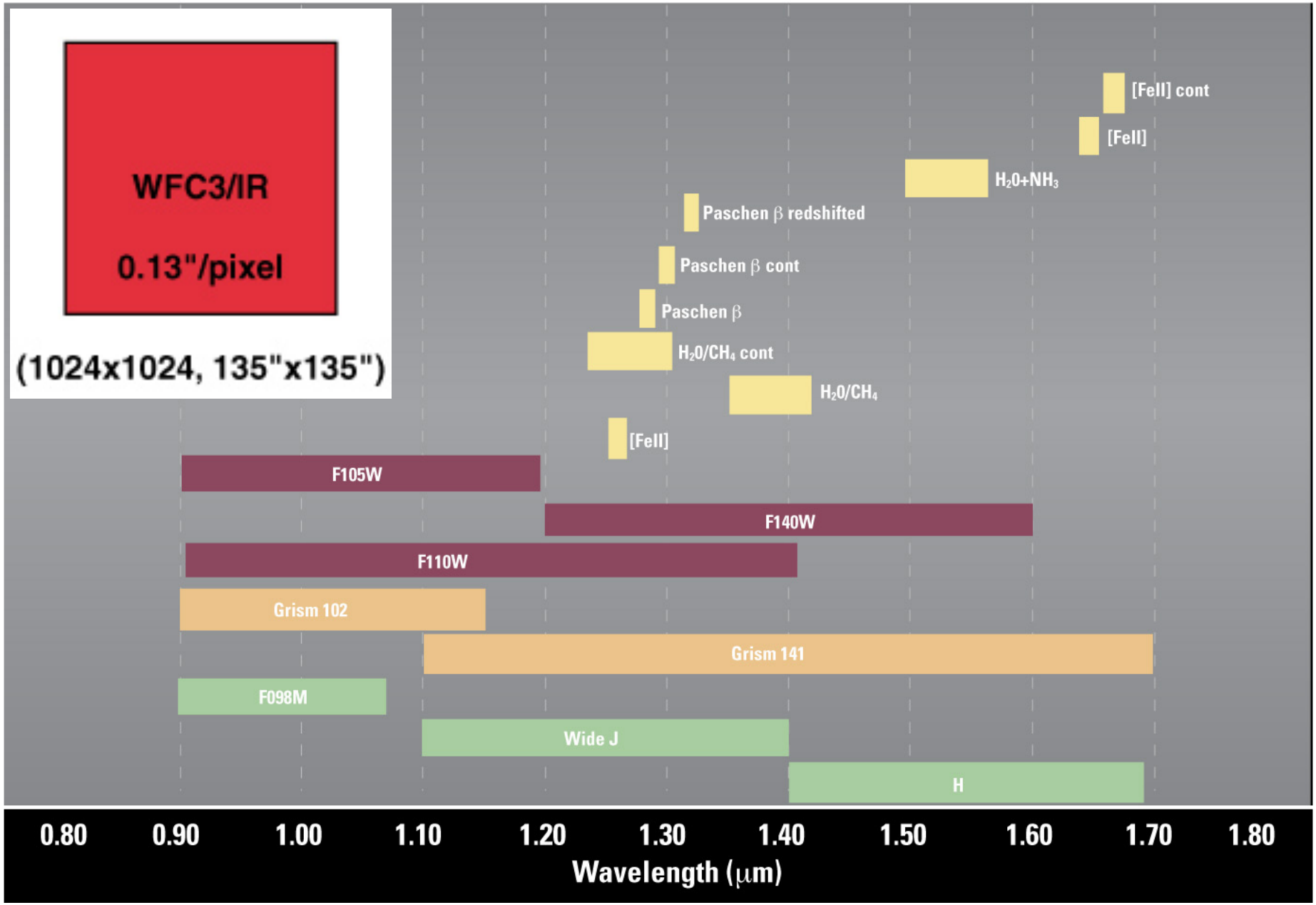
UVIS Channel





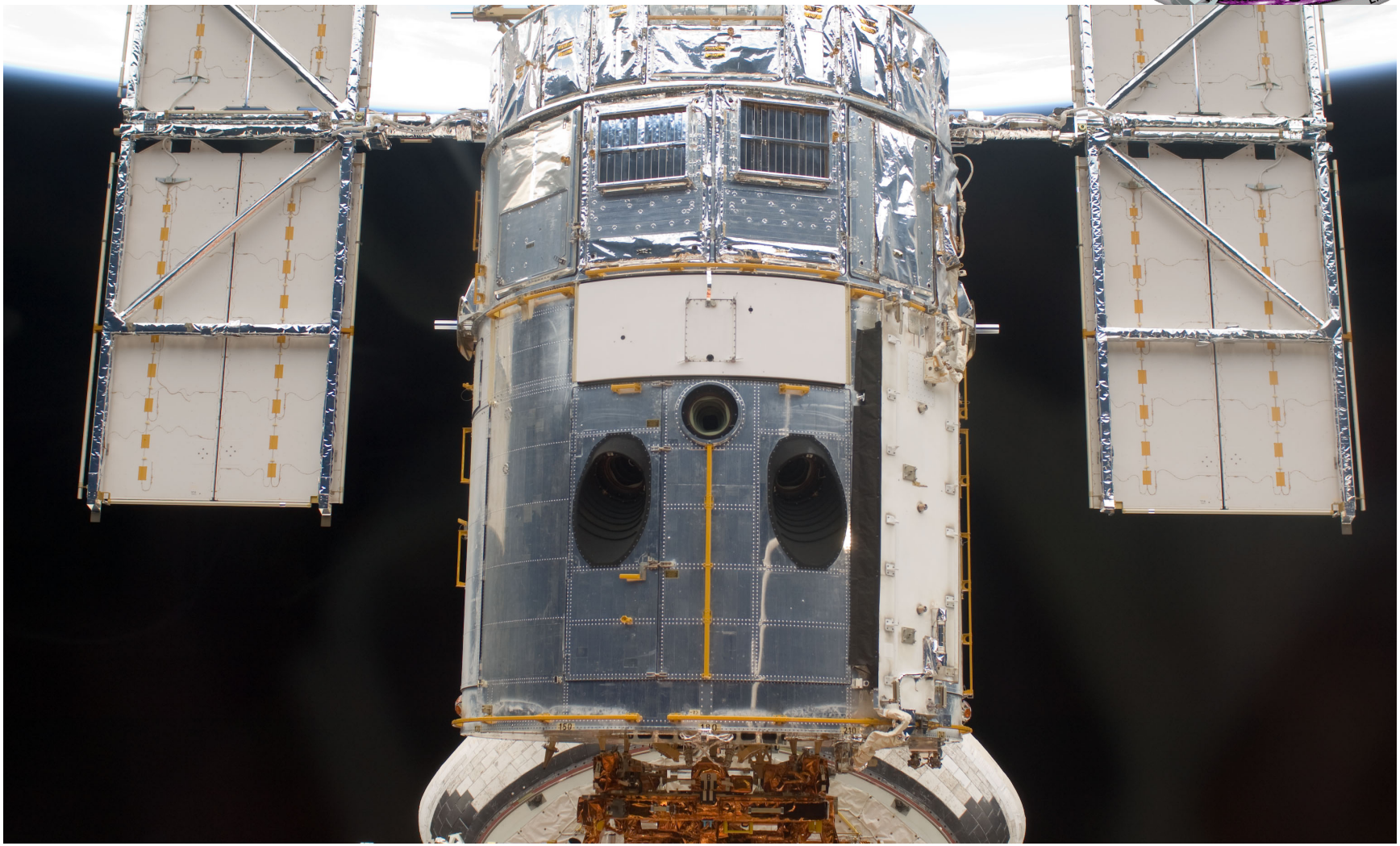
2 CCDs, 4 amplifiers, 5 filter wheels
62 filters – broad band, medium band, narrow band, monolithic and ‘quad’
1 grism


UVIS
z(Ha+[NII])
[SII]
[SII]+z(Hα)
z(Ha+[NII])
[NII]
Hα
Continuum
[OI]+[SIII]
[OII]
[Ne IV]
z[OII]
[OIII]
[NeIII]
[OIII]
zHβ
cont.
[OIII]
Hβ
HeII
Call H&K
[OII]
[NeV]
MgII
z[OIII]
[NII]
[SII]
[SII]
CH4
cont.
CH4
cont.
CH4
2.5 km-agt
25 km-agt
0.025 km-agt
0.25 hm-agt
F845M
F763M
F689M
F621M
y
b
v
F390M
F600LP
F475X
F300X
F200LP
F350LP
SDSS z'
SDSS i'
SDSS r'
SDSS g'
WFPC2 Wide I
UV Grism
WFPC2 Wide V
WFPC2 V
WFPC2 B
F390W
U, u
F275W
F225W
F218W
100
200
300
400
500
600
700
800
900
1000
1100


WFC3/IR
0.13"/pixel
(1024x1024, 135"x135")
[FeII] cont
[FeII]
H2O+NH3
Paschen β redshifted
Paschen β cont
Paschen β
H2O/CH4 cont
H2O/CH4
[FeII]
F105W
F140W
F110W
Grism 102
Grism 141
F098M
Wide J
H
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
Wavelength (μm)

Canada

WFC3 in HST



Pre-Flight Calibration

- Thermal Vaccuum tests
  - fully assembled instrument placed in thermal and vaccuum controlled test chamber
  - operated in simulated flight conditions
  - calibrated light source(s) puts light into the optical path of the instrument
    - CASTLE (Calibration Stimulus from Leftover Equipment)

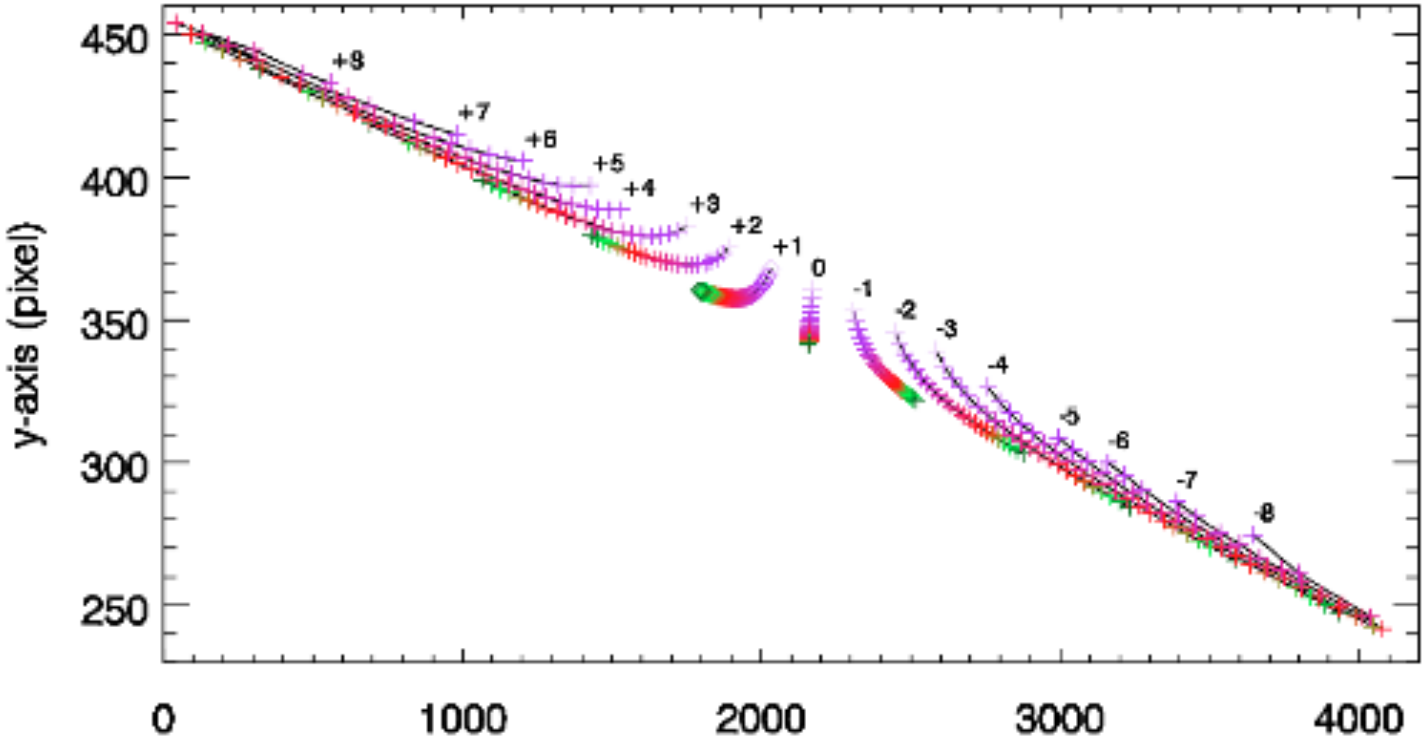
Pre-flight Ground Testing

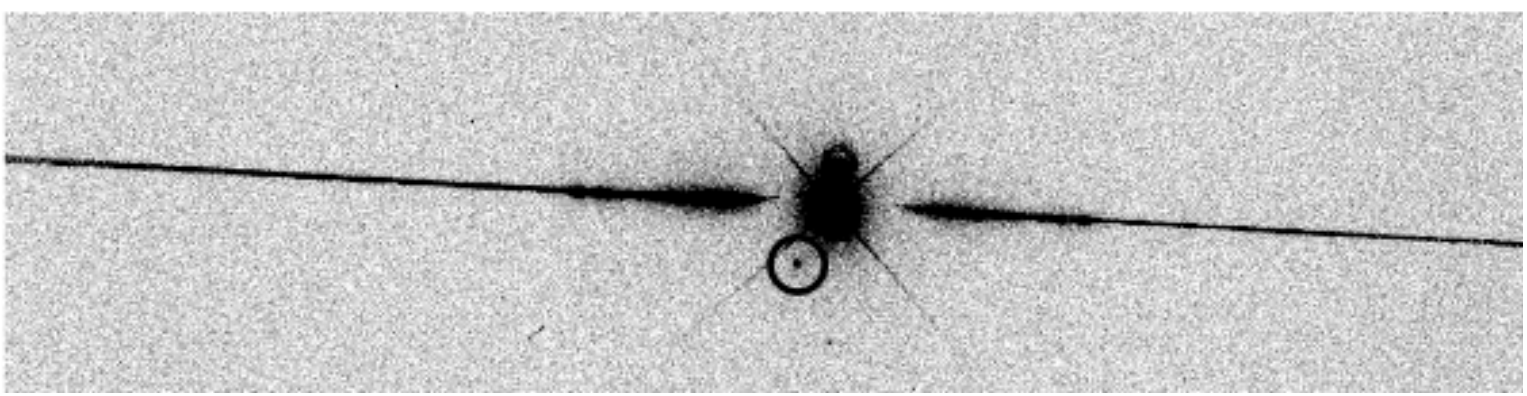
TV2 & TV3 provide:

- initial set of dark and bias files
- initial flat fields for all filters
- the only spectroscopic flat fields
  - monochromatic flats
- checks on the
  - wavelength response
  - filter transmission
- detector characteristics:
  - Readnoise
  - Intrapixel sensitivity variation
  - Quantum efficiency
  - Hysteresis (Bowtie)
  - Persistence

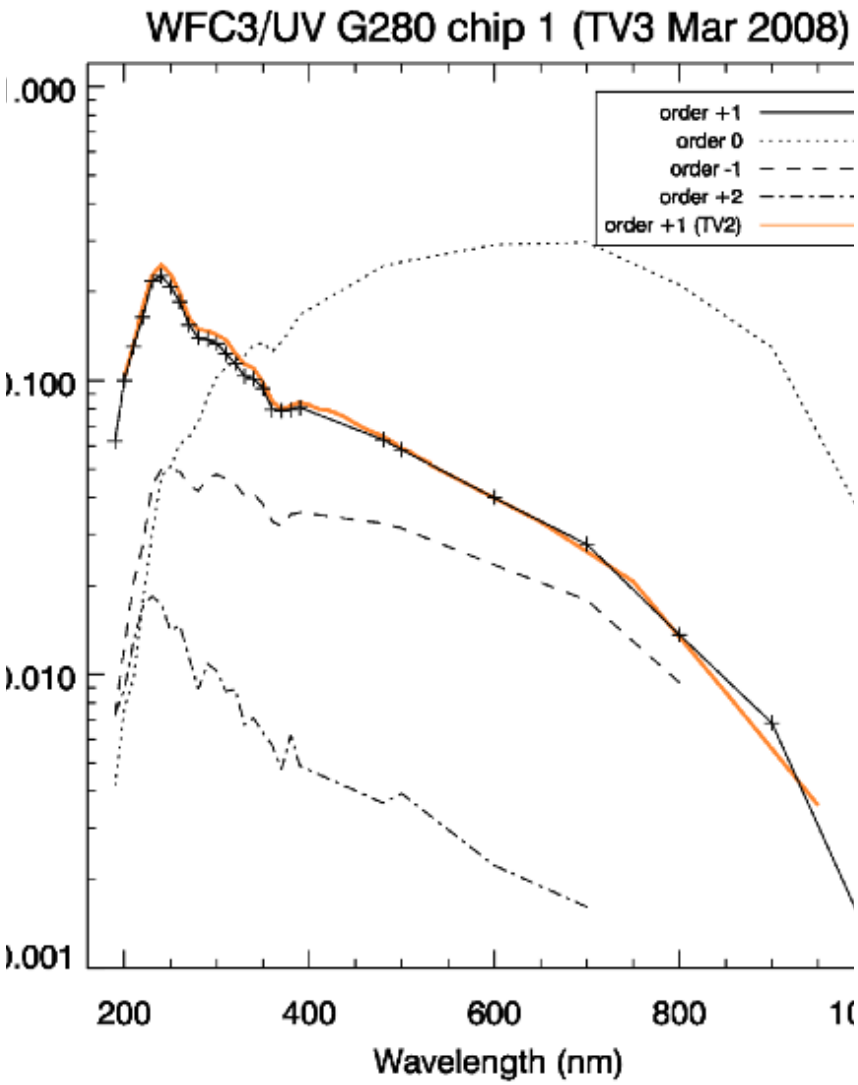
Pre-flight data provides first pass to development of the ETC, and Synphot, used subsequently to develop observing programs

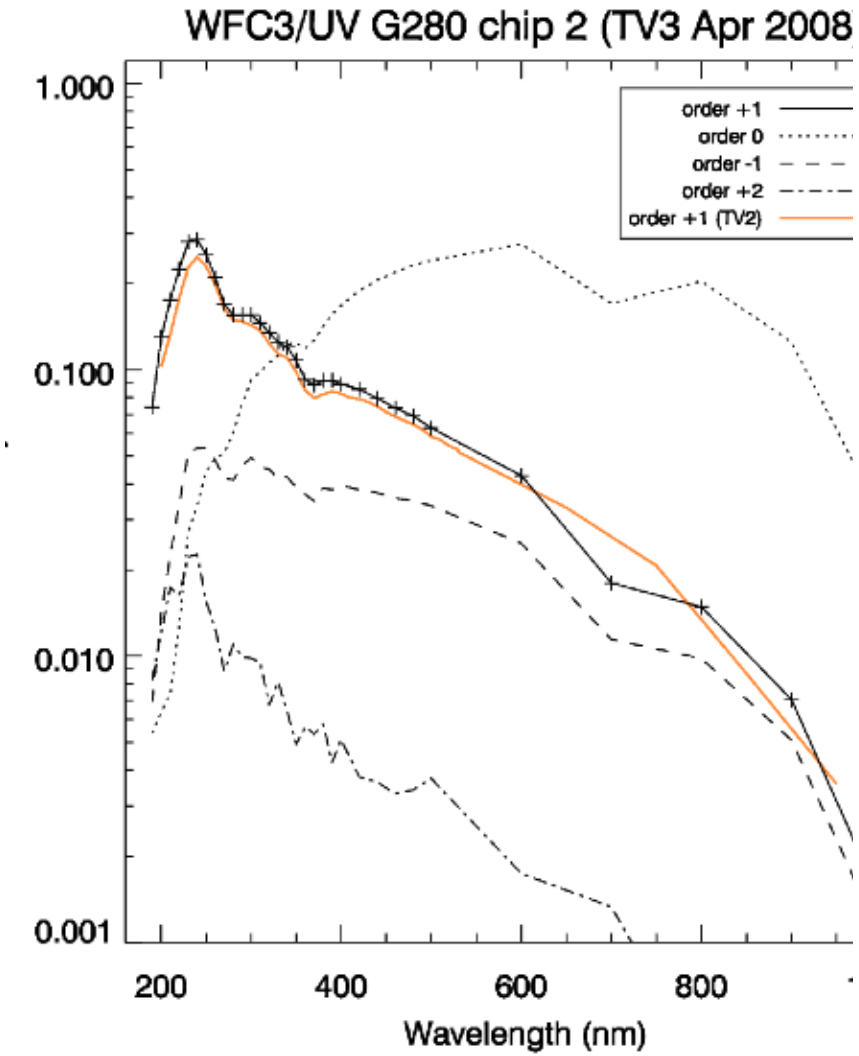
G280 Grism TV3





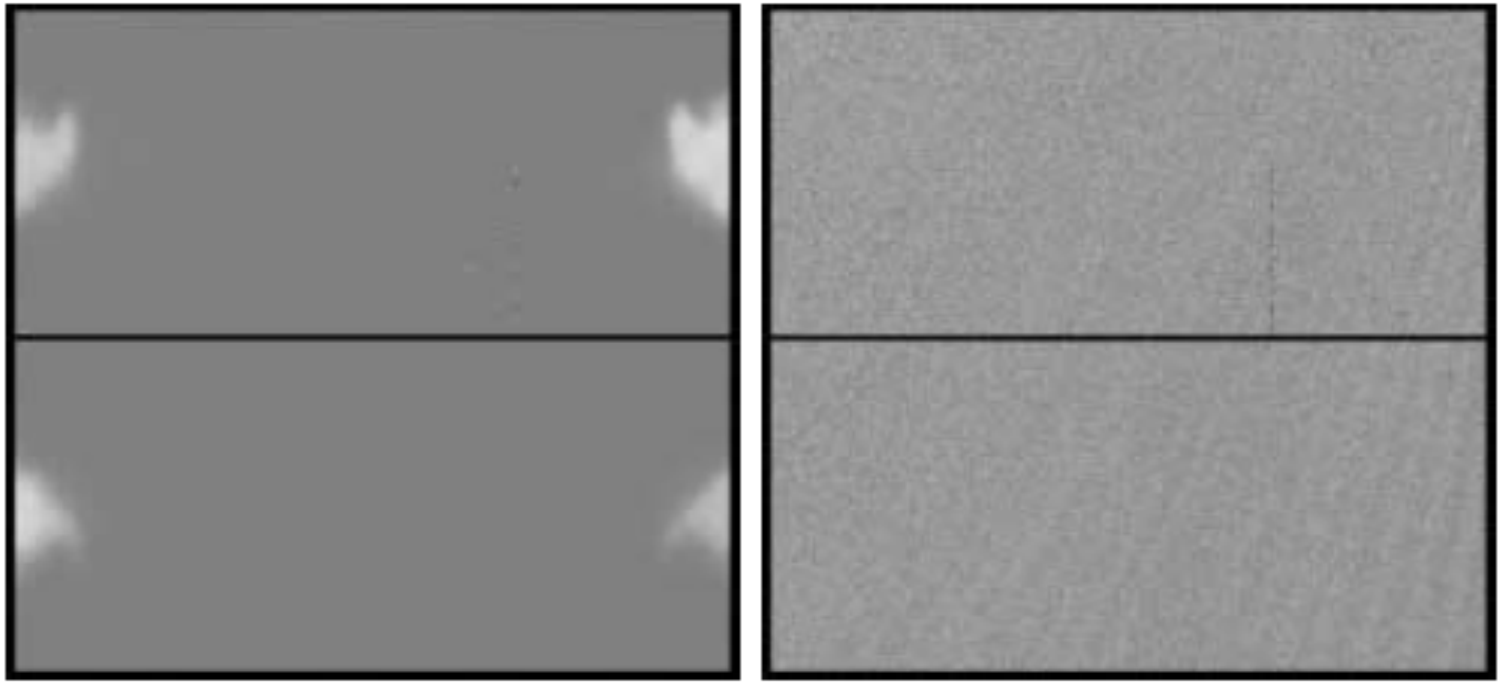
UVIS Grism G280- TV3



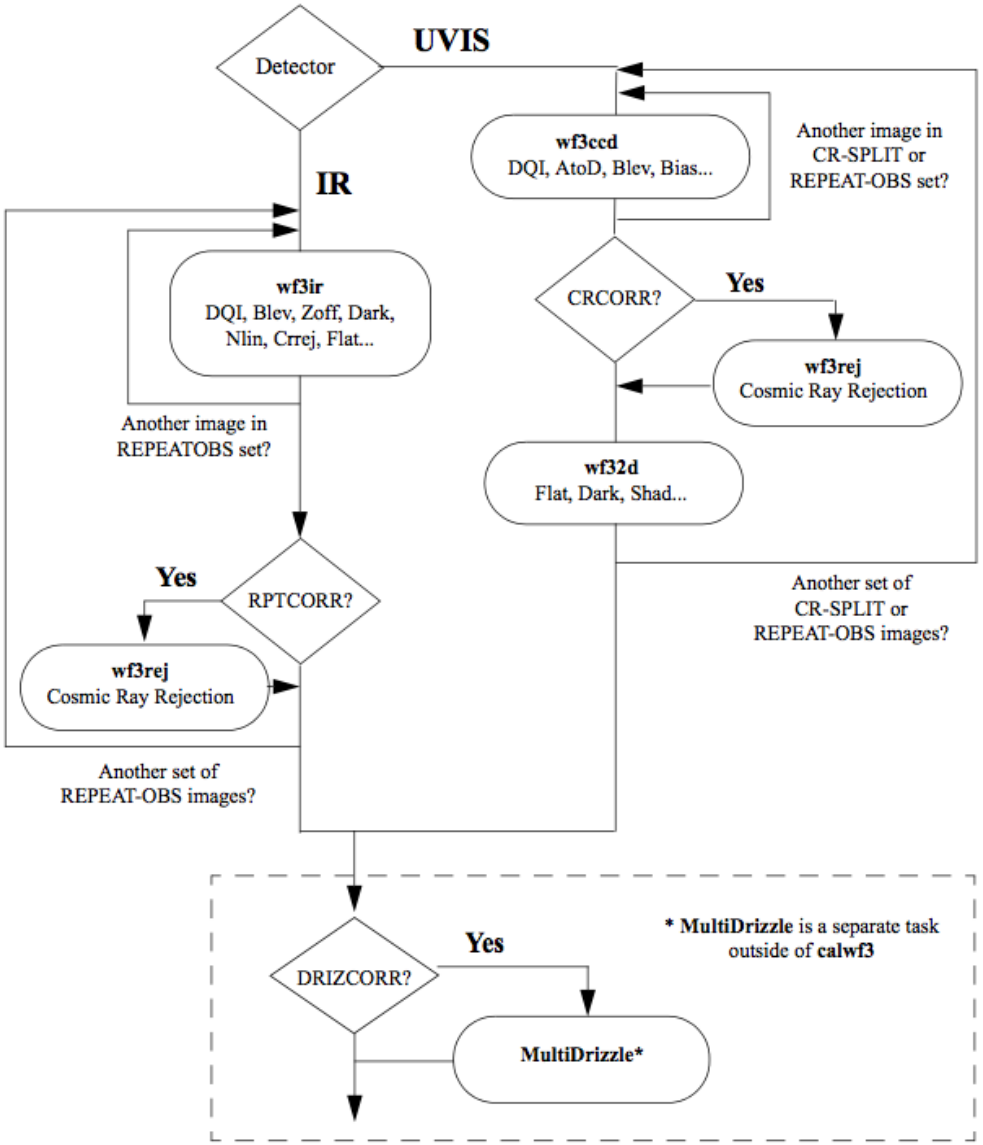


“bowtie” and shutter edge effect

Figure 2: At right is a hard stretch (+/-1%) of an image ratio of two F814W images taken within 14 hours of each other, illustrating low-level shutter edge effects (the slanted lines which appear to emanate from the upper right, B amp corner). At left is an image ratio of two F555W images taken about 26 hours apart, showing the CCD ‘hysteresis’ effect. Stretch is +/-10%.



Data processing Flow Chart



In-Flight Calibration Activities

- SMOV
  - Service Mission Observatory Verification
  - Service Mission 4B in May 2009
  - 3 month commissioning May – August 2009
- Regular Cycle Programs
  - Cycle 17 ~9/2009 – 8/2010
  - Cycle 18 ~9/2010 – 8/2011
  - Cycle 19 ~9/2011 – 8/2012
  - Cycle 20 ~/2012 – 8/2013
    - NB: Cycle 'boundaries' are fuzzy

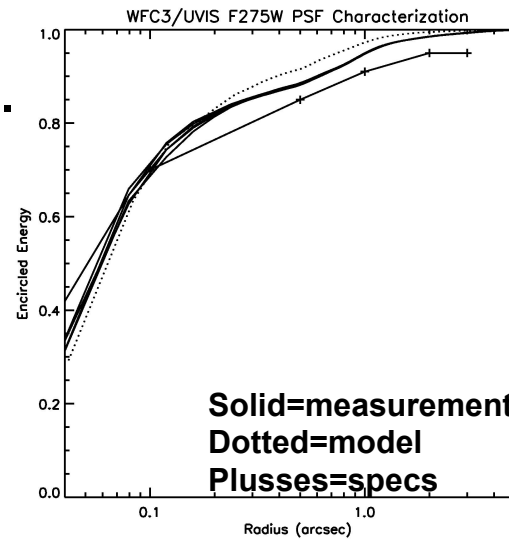
SMOV – Service Mission Observatory Verification (May – Aug 2009)

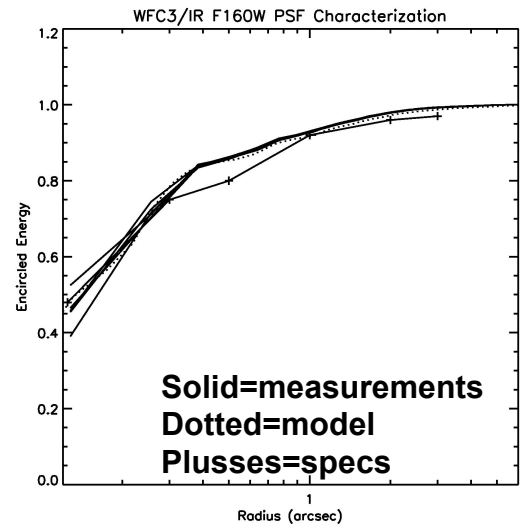
- Basic operation checkout
- First light image
- Initial checks on throughput, image quality, flat fields, linearity, zeropoints, bad pixels.
- Establish baseline for darks, biases, charge transfer efficiency, sensitivity (stability).
- Fringing test – jupiter impact
- => nominal behavior, met specs.

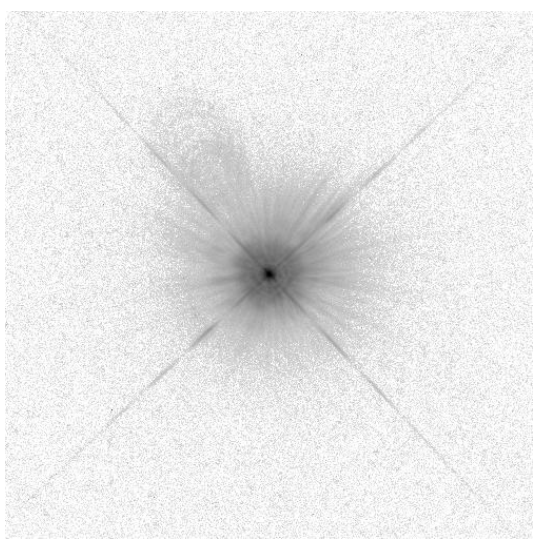
PSF Characterization

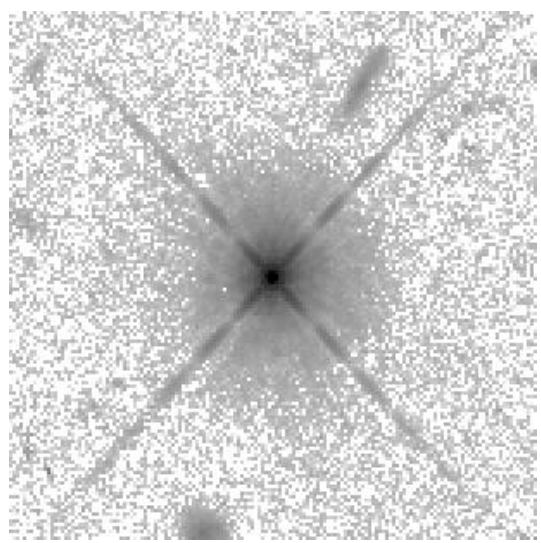
Encircled energy vs. Radius (arcsec)

Left: UVIS F275
Right: IR F160W









PSF WINGS

Left: UVIS F275W
Right: IR F160W

20 x 20 arcsec,
6 dex log stretch

Read Noise Improved vs. Ground Test

- CDS read noise is 20-22 e- rms (varies with quadrant); same as ground result; noise in RAPID reads also similar to T-V result
- Effective noise reading up the ramp is actually a bit lower in flight than in thermal-vac for long exposures: (average of the 4 quadrants shown)

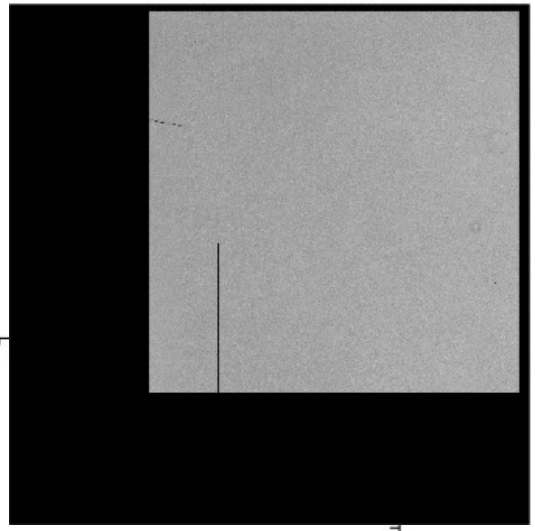
# of Reads	3	8	15
Effective noise (e- rms; SMOV)	19.6	16.0	12.4
Effective noise (e- rms; thermal-vac)	20.8	17.8	14.6

For SPARS200 sample sequence

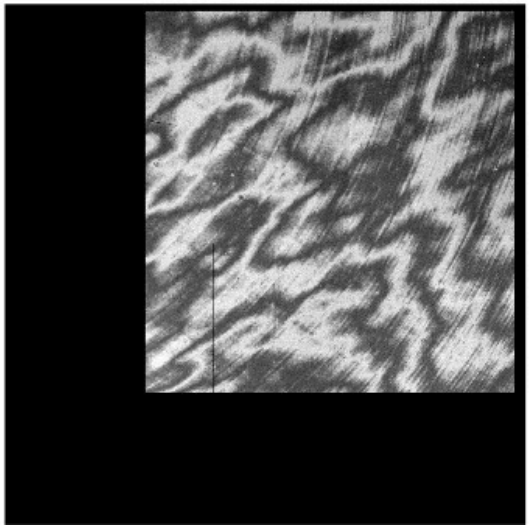
- *Combined with excellent dark current, very well satisfies goal of being zodiacal-background-limited for long exposures in broad bands (zodi rates from a few tenths to >1 e-/pix/s)*

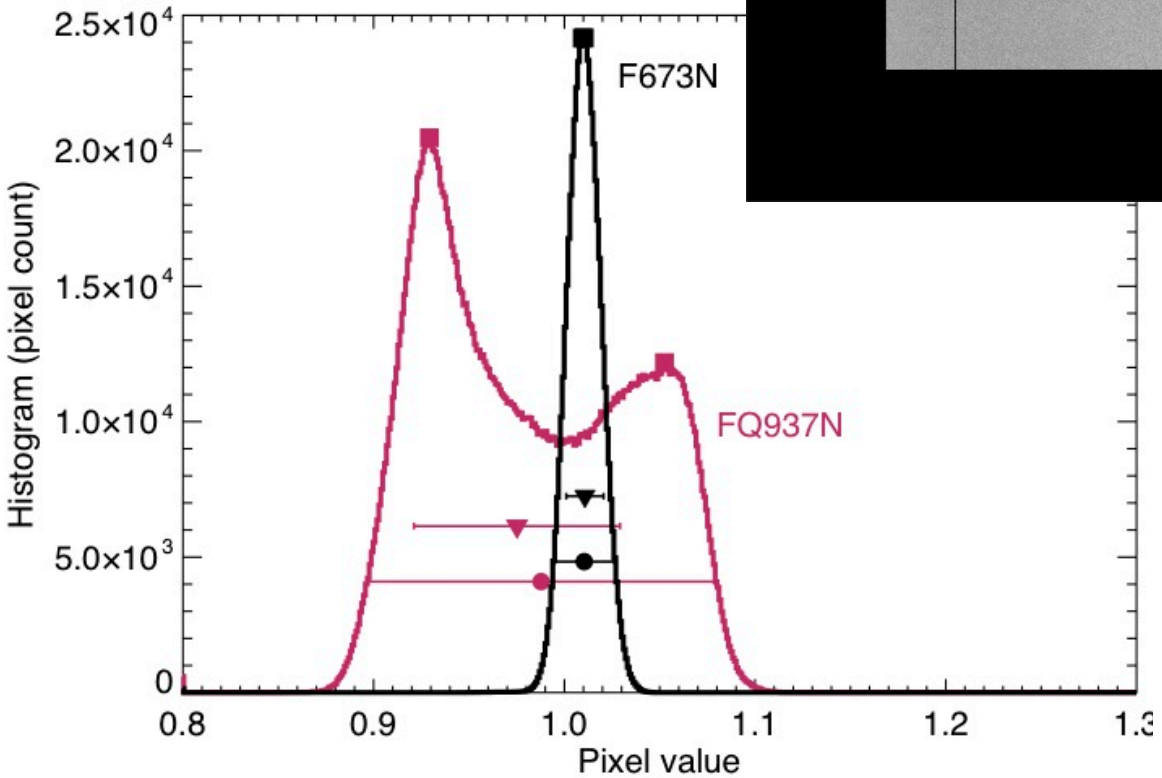
Fringing in CCDs

F673N flat field (quadrant B)

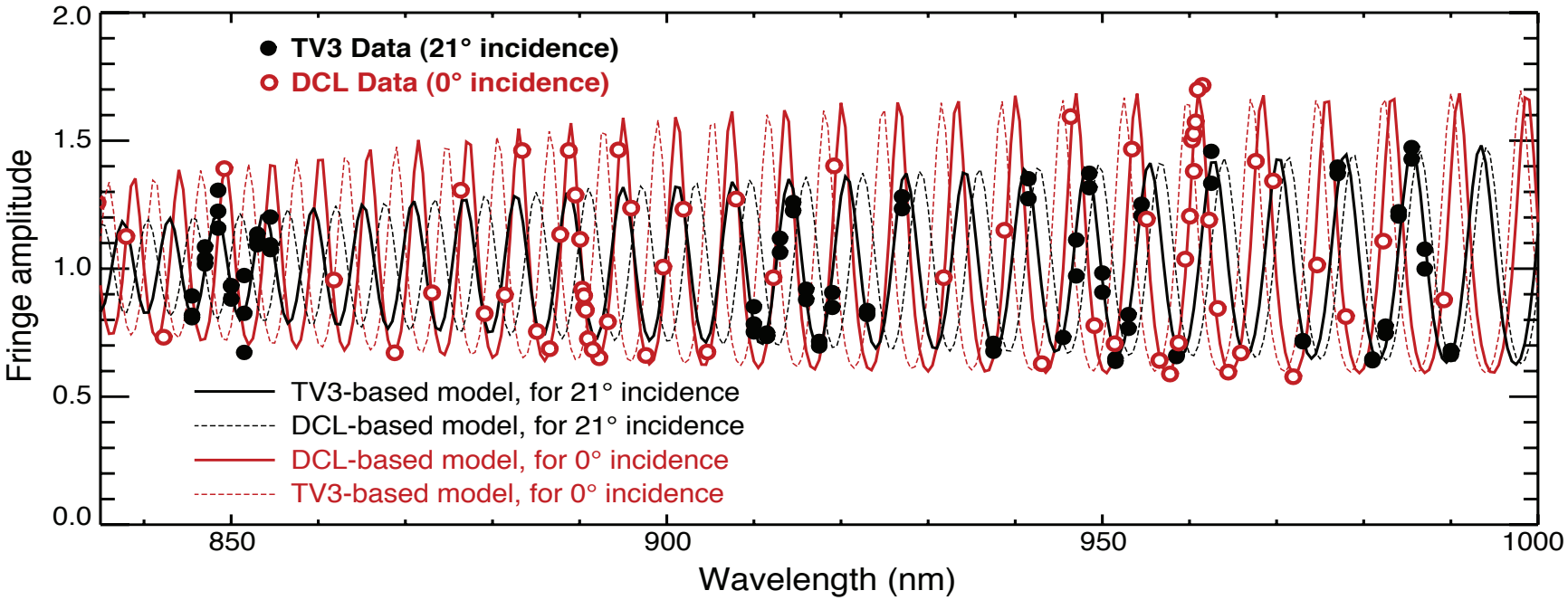


FQ937N flat field (quadrant B)

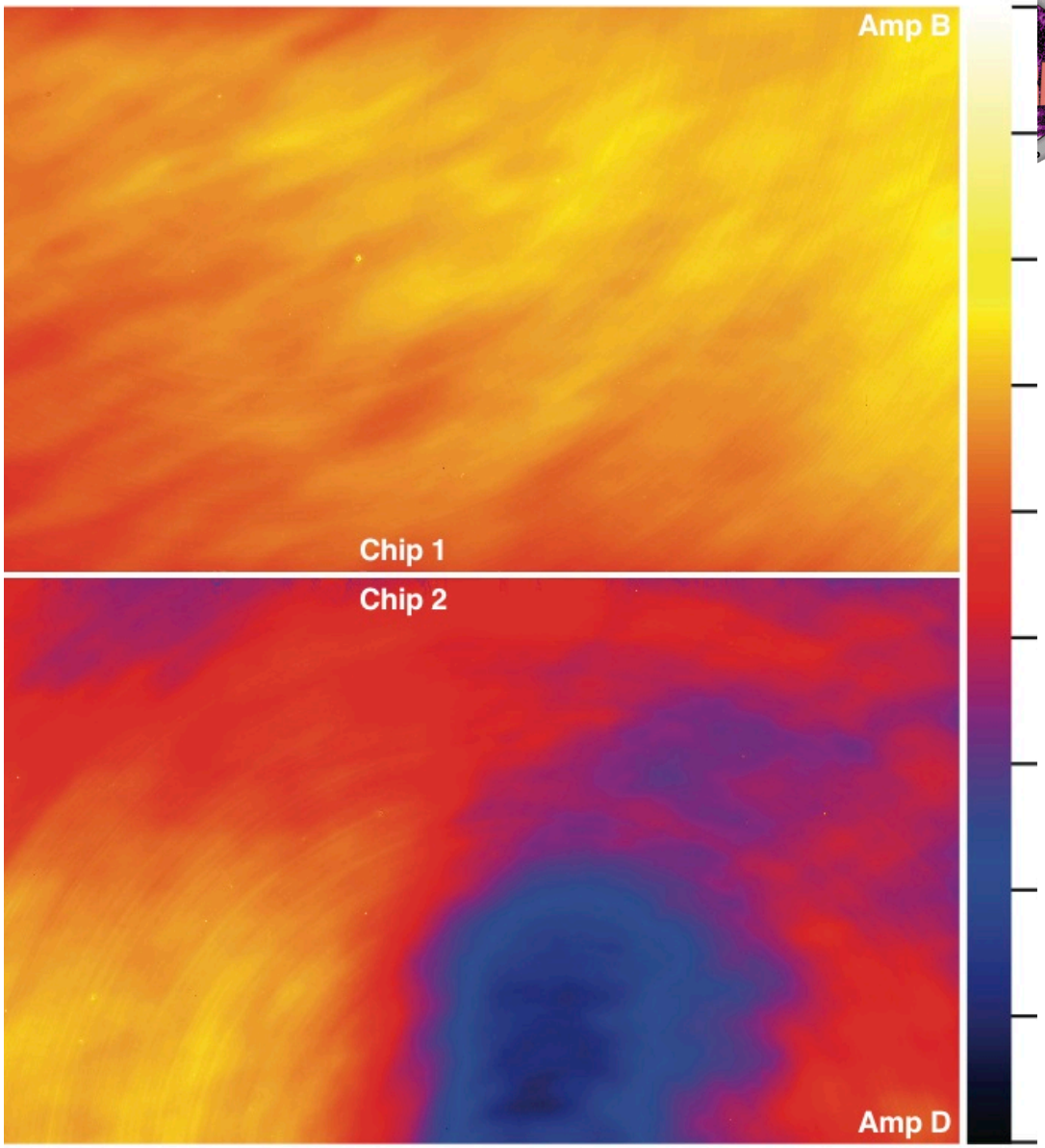




Fringe model vs. data



Detector thickness



Post SM4 Calibration Activities

- Monitor instrument behavior
  - CCD
    - Charge transfer efficiency
    - Readnoise
    - Pixel response
    - Linearity
    - Geometric distortion
    - Image quality (PSF)
  - HgCdTl
    - Intrapixel variation
    - Linearity
    - Count rate non-linearity
    - Geometric distortion
    - Image quality (PSF)
  - Contamination
    - UV, outgassing
  - Photometric stability
    - Zeropoints
    - Flat fields – pixel to pixel, low frequency spatial variation

Building Calibration Programs

- Goal:
  - Provide calibrations to match PI science objectives and optimize HST / WFC3 science

	Cy17	Cy18	Cy19
WFC3 of HST total	46.1	41.9	48
IR Imaging	24.4	5.5	11.4
IR spectroscopy	6.7	15.9	2.7
UVIS imaging	15	15	26.4
UVIS spectroscopy	<1	<1	0.9

as percentage of total HST orbits per cycle

Building Calibration Programs

- Daily
  - Dark frames – for each detector, subarray and exposure modes
  - Biases –> superbiases
- Weekly
  - flats – for every filter utilized
    - internal tungsten lamps
    - star clusters
- Monthly
  - anneals
- Least Frequent:
  - monitoring programs, new programs
    - wavelength calibration
    - flux calibration for each detector, filter & grism
    - photometric stability
    - geometric distortion, PSF
    - persistence
    - charge transfer inefficiency
    - UV contamination

Building Calibration Programs

Calibration Sources:

1. Lamps (QTH & Deuterium))
2. Basic Set of Astrophysical sources
    1. Omega Cen
    2. 47 Tuc
    3. GD73, GD153, G191B2B, P330E, & GRW70

Calibration Hardware:

back of the channel select mechanism

otherwise None!

Cycle 17 Activities

Primary programs

- characterization of
  - geometric distortion,
  - zeropoints,
  - sensitivity
  - filter transformations;
- daily monitors
  - detector gain,
  - darks and biases;
- monthly anneals (CCDs),
- "bowtie" pinning
- checks on persistence on the IR detector (MCT),
- count rate nonlinearity
- flats.

Additional checks on

- IR persistence
- Additional fringe calibration
- Check subarray linearity
- Determine image skew wrt to fixed stars – astrometry
- Stray light
- Test spatial scanning mode

Orbit allocation

- 256 external orbits
- 2000+ internal orbits

Cycle 18 Programs

- Regular monitor programs – darks, bias, anneal, stability, bowtie
- Expand photometric standard sets– more spectral types
- improve color transformations
- calibration of scanning modes – photometry and spectroscopy (enables bright object to V~0mag)
- high contrast imaging tests (e.g. exoplanets)

Additional tests for

- persistence – correction file
- flat field tests – raster scanning of a standard star.
- CTE mitigation

- ~150 external orbits,
- ~1900 internal orbits

Cycle 19 Programs

- Regular monitor programs – darks, bias, anneal, stability, bowtie
- photometric calibration ladder
- calibration of scanning modes minus orders (flux, wavelength)
- spatial scans of stars to test flat fields and improve astrometry
- earth flats

Additional tests for

- Charge injection (mitigate CTE)

~125 external orbits
~1587 internal orbits

So, What Do We Know?

Count Rate Non Linearity WFC3 - NIC

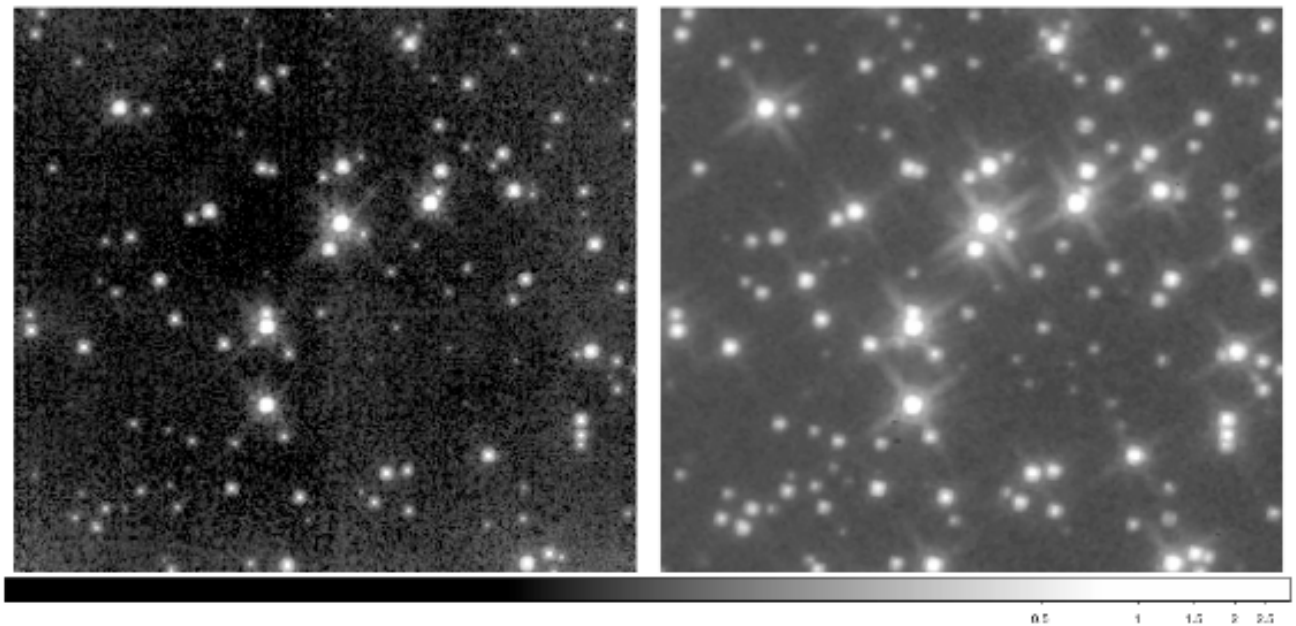


Figure 1: NIC2 field in 47Tuc F110W (left) and corresponding region in WFC3-IR F110W (right).

Count rate non linearity ('reciprocity failure')

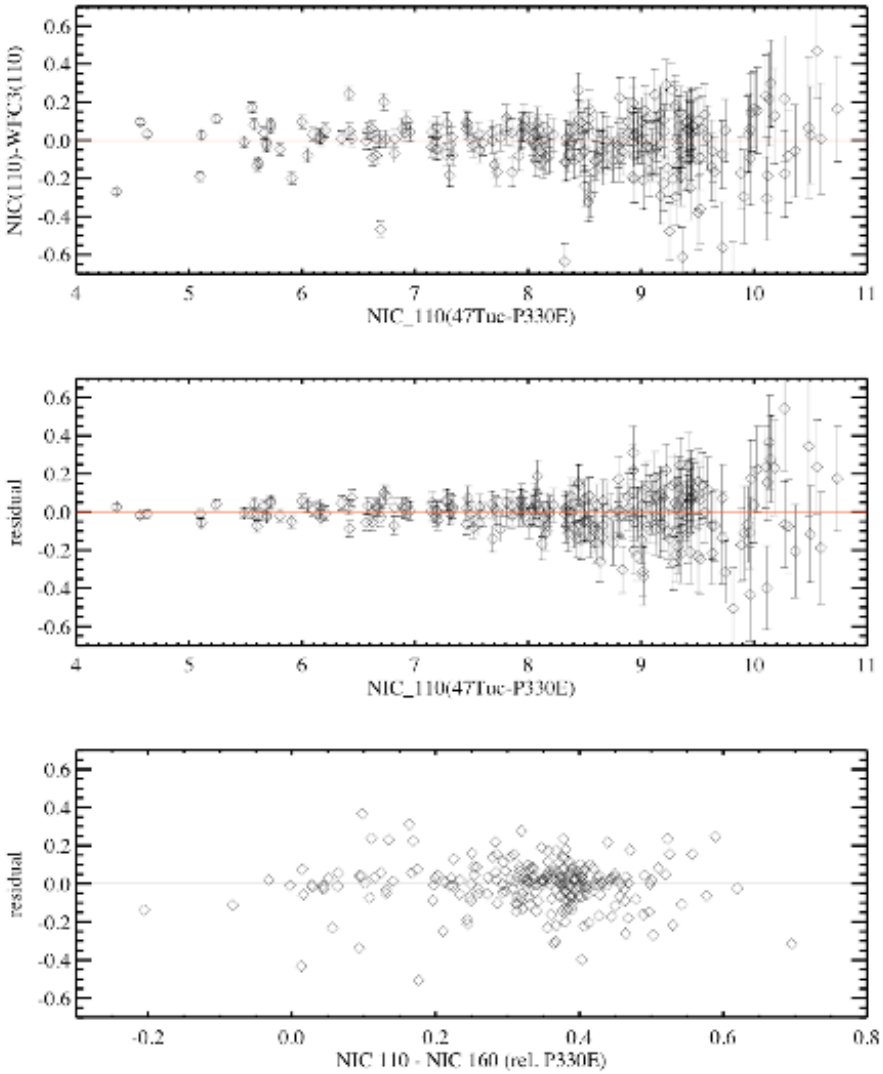
depends on brightness and wavelength of source

bright sources are brighter

faint sources are fainter

i.e. 10 x 100 ≠ 100 x 10

Count Rate Non Linearity WFC3 - NIC



Results:

- F110W:

0.01 +/- 0.0022 mag/dex

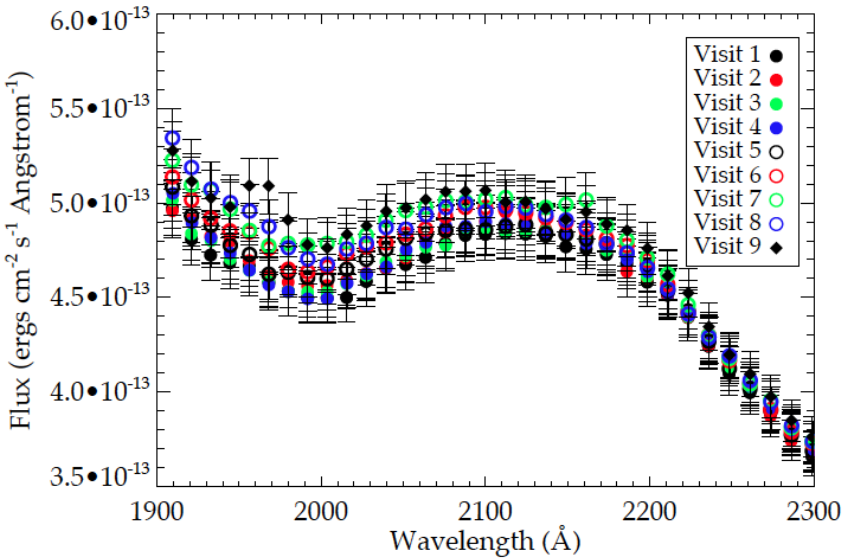
- F160W:

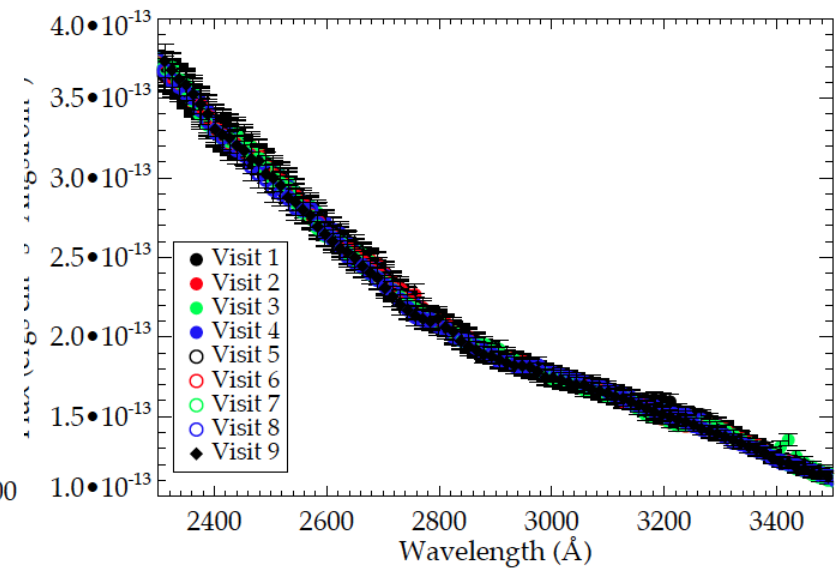
0.011 +/- 0.0022 mag/dex

- F098M:

-0.065 +/- 0.0031 mag/dex

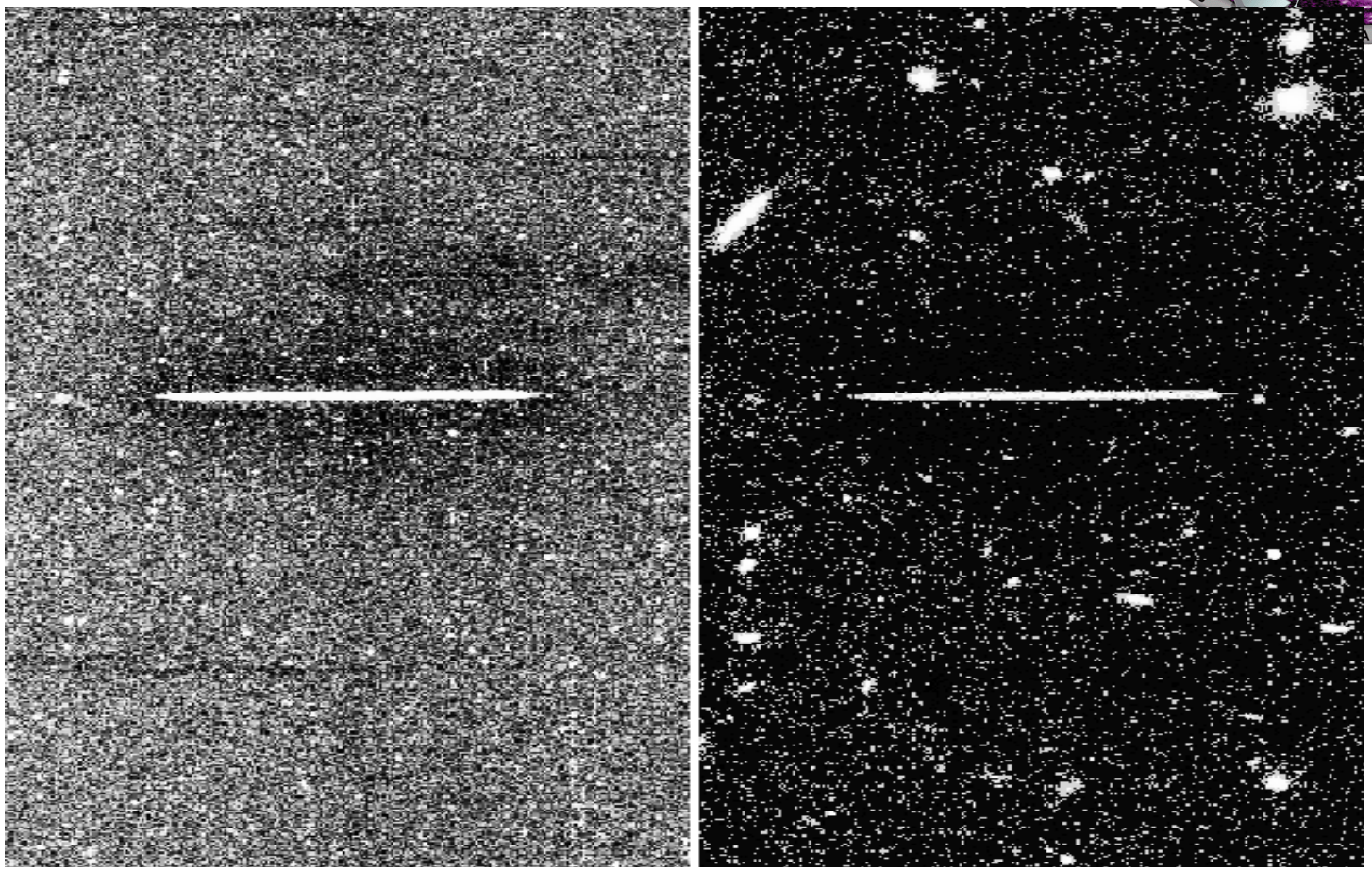
UVIS Contamination





Observations over 7 epochs show no statistical change in the UV response. Errors bars are formal statistical errors.

Persistence



LHS: guard dark, RHS: an MCT observation
Grism observation was taken 1 hour before

Persistence

Latency

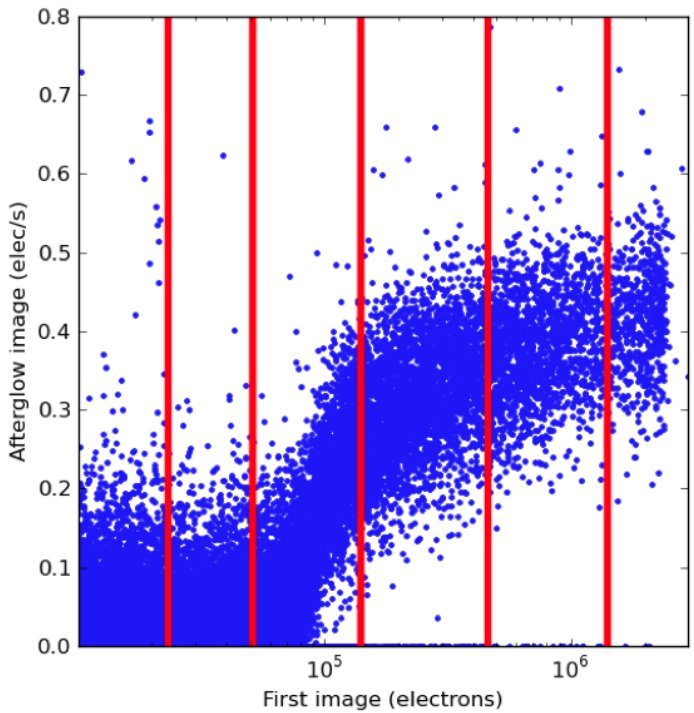
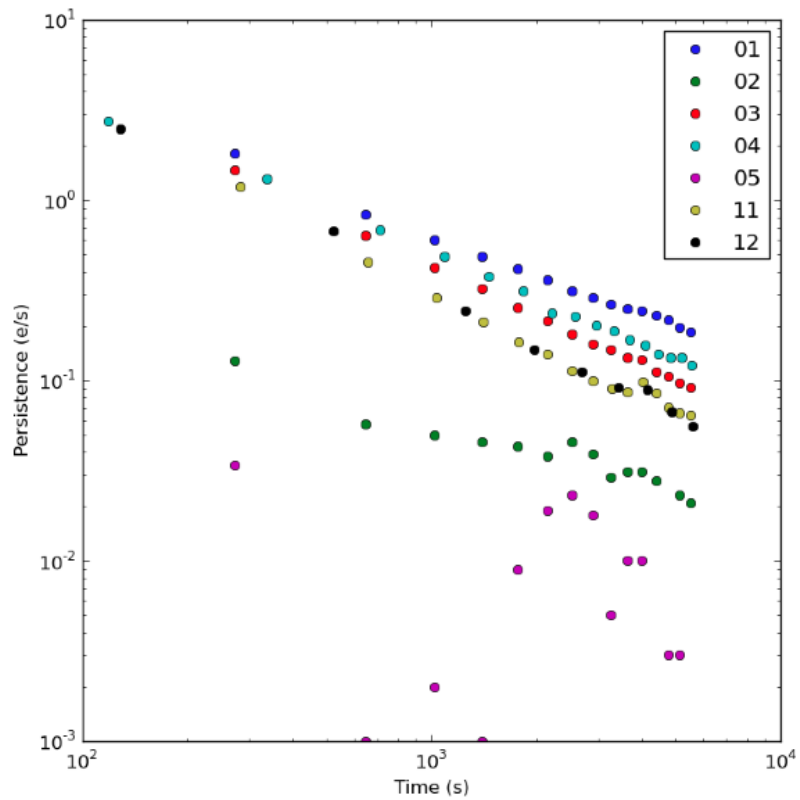
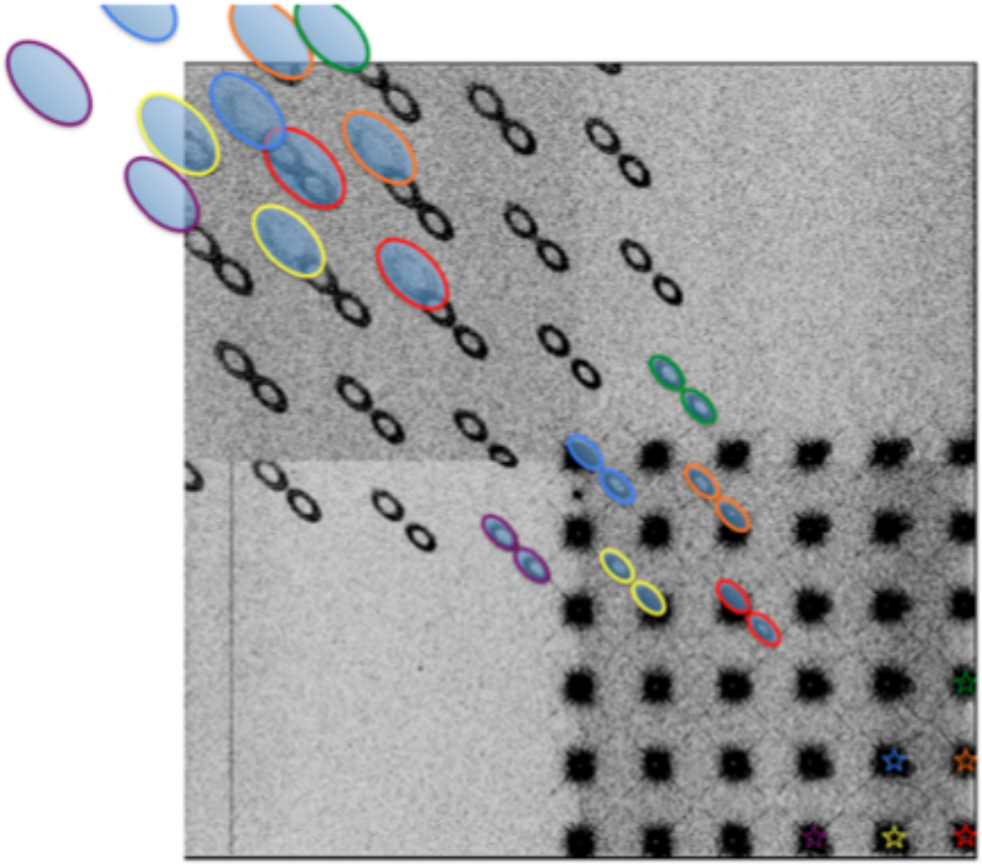


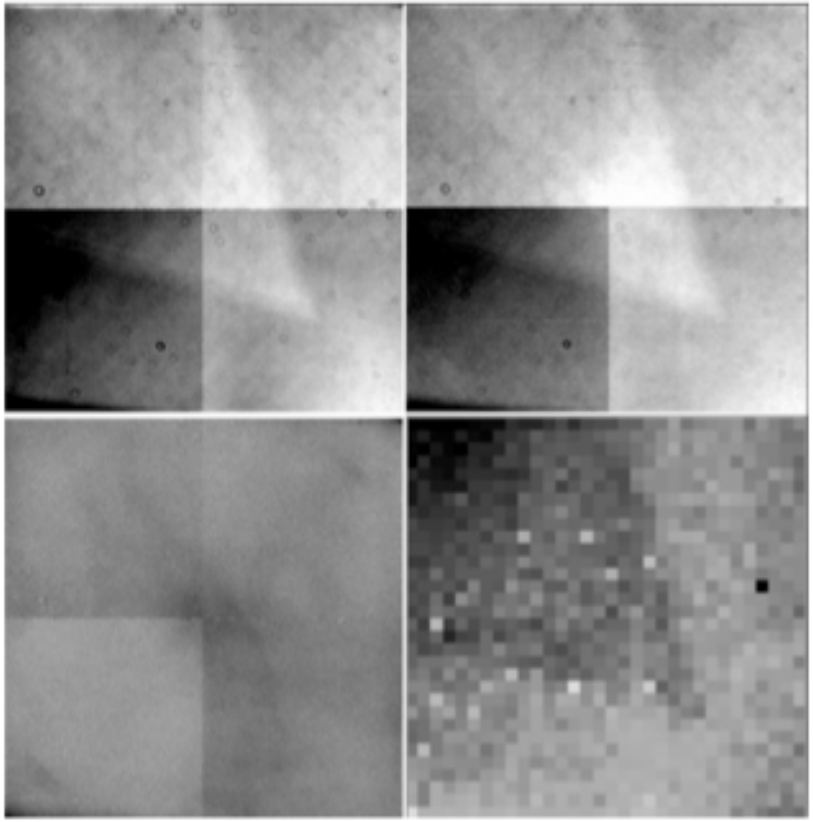
Figure 1 - The persistence as observed individusl pixels in a Dark exposure shortly after the IR deector had been illuminated by a very bright star, in this case Fomalhaut. The x-axis shows the illumination in electrons of the last of the Fomalhaut exposures while the y-axis shows the persistence in e s^{-1}. The red vertical lines shows the five levels to which the array was illuminated with the Tungsten lamp in this calibration program.

Decay rates

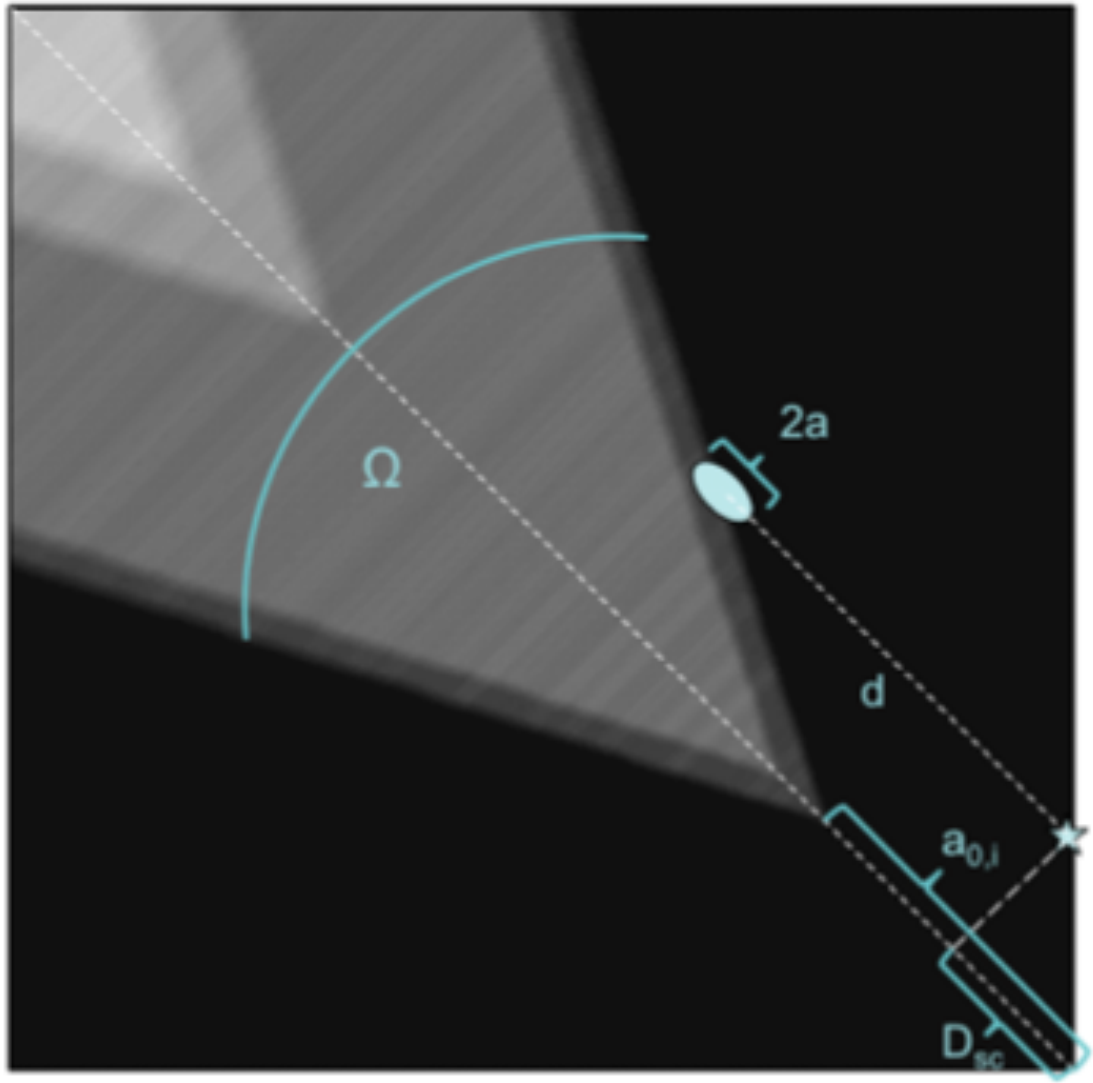


Flat fields and Ghosts

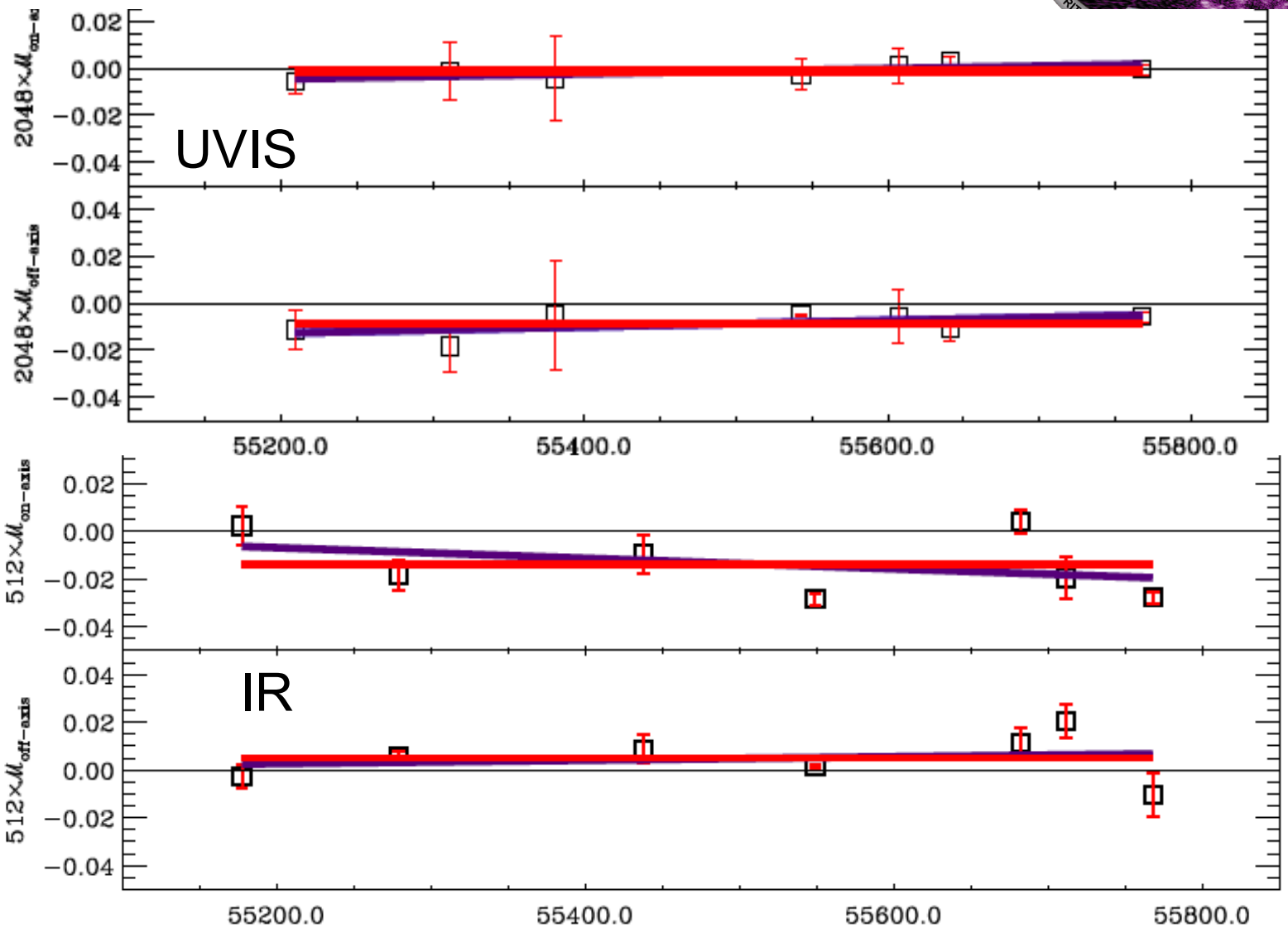




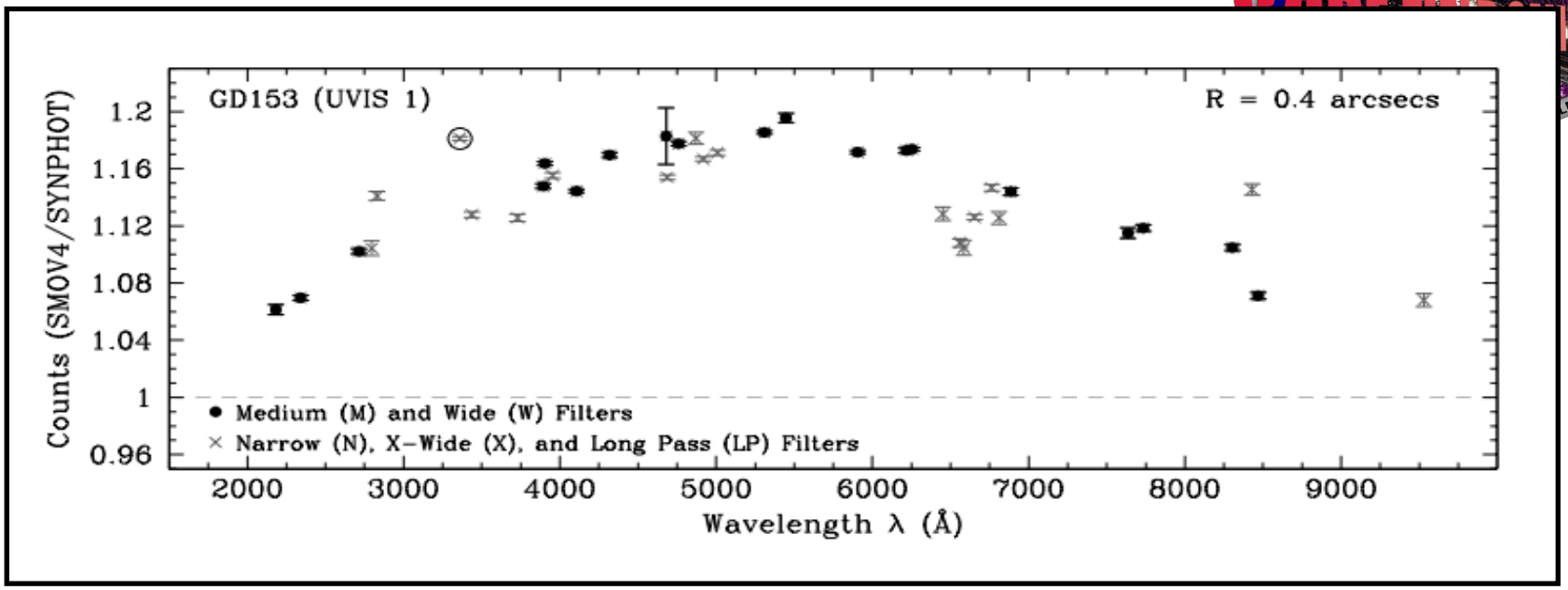
Model of Ghost Flares



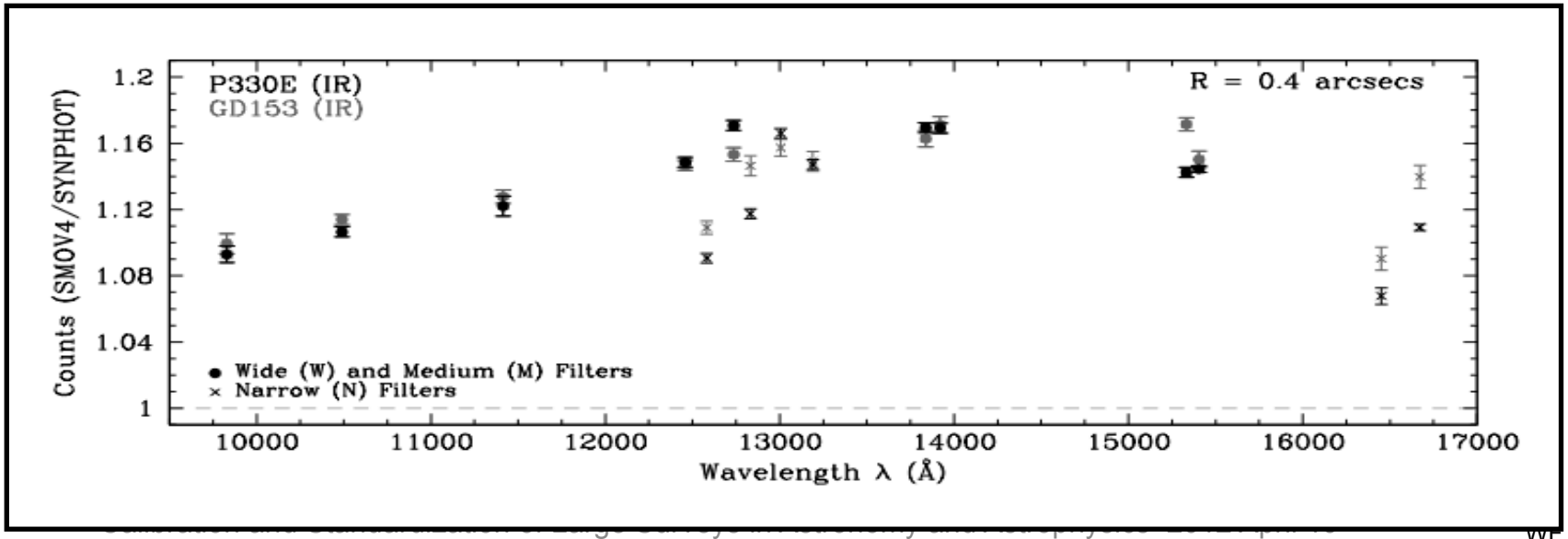
Linear Distortion stability



Observed vs. Predicted Sensitivity

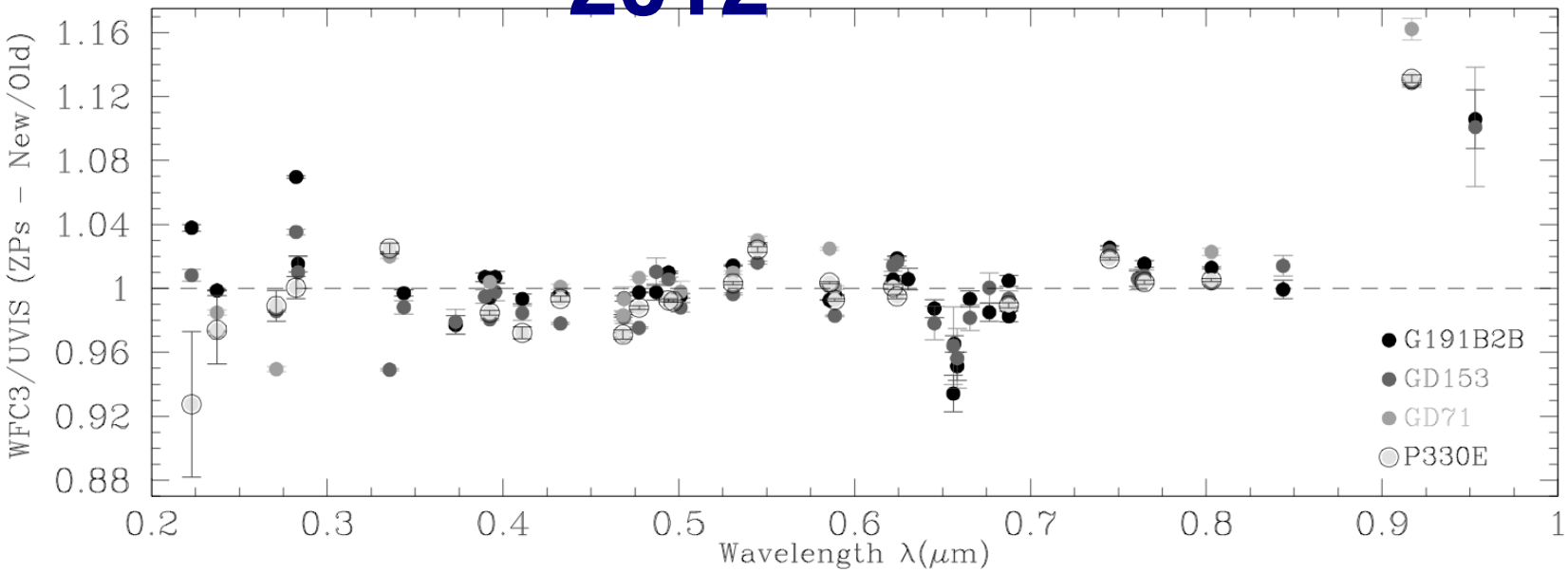


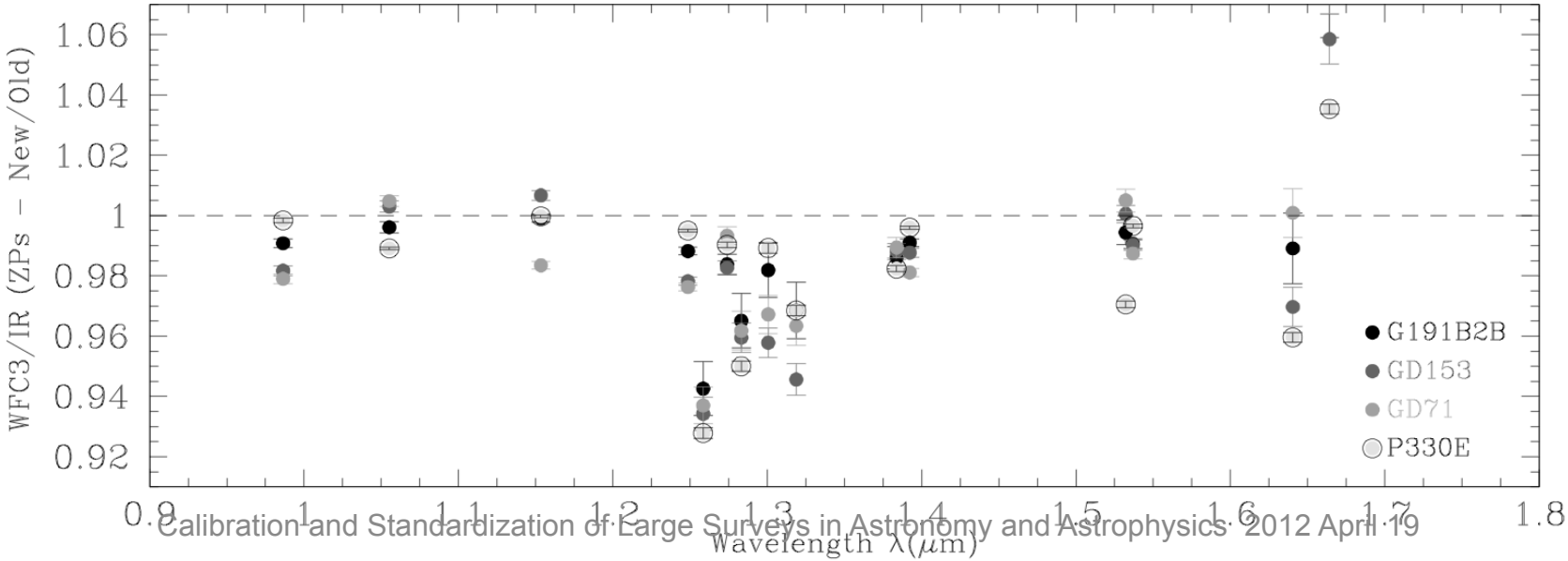
UVIS: 5-10% boost in efficiency at blue/red λ's, 15-20% at 400-700 nm



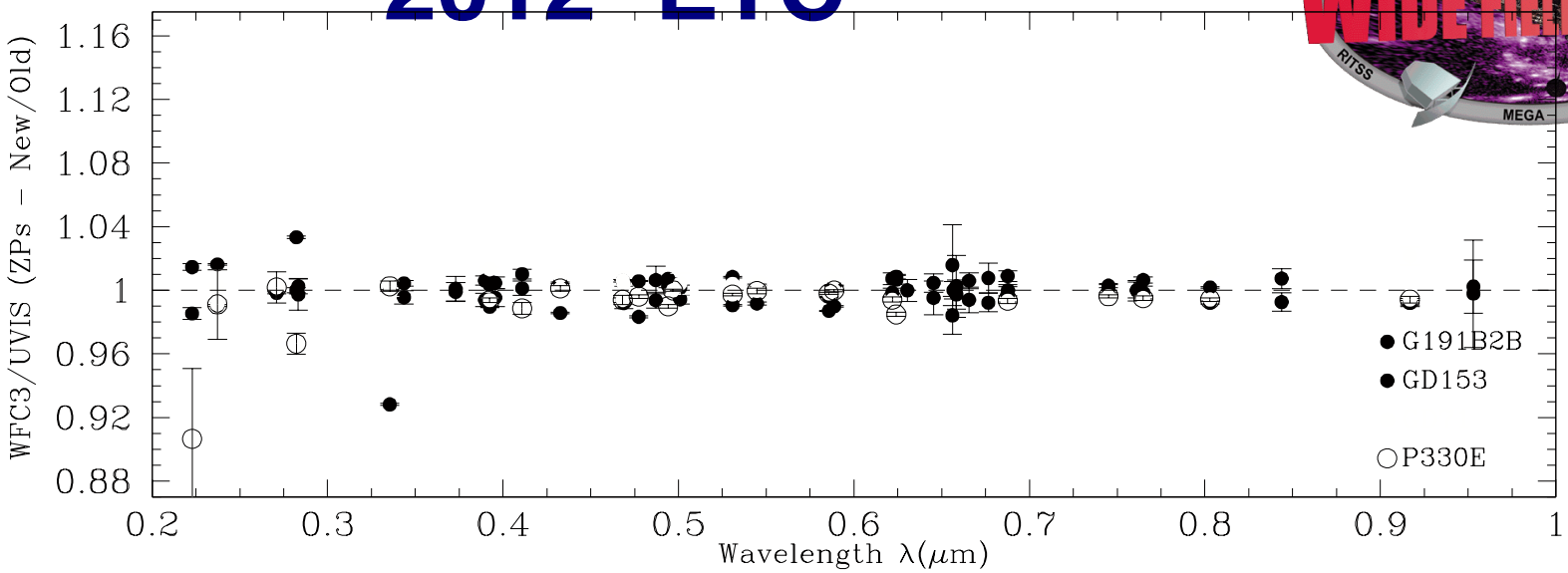
IR: 10-15% boost in efficiency at all λ's

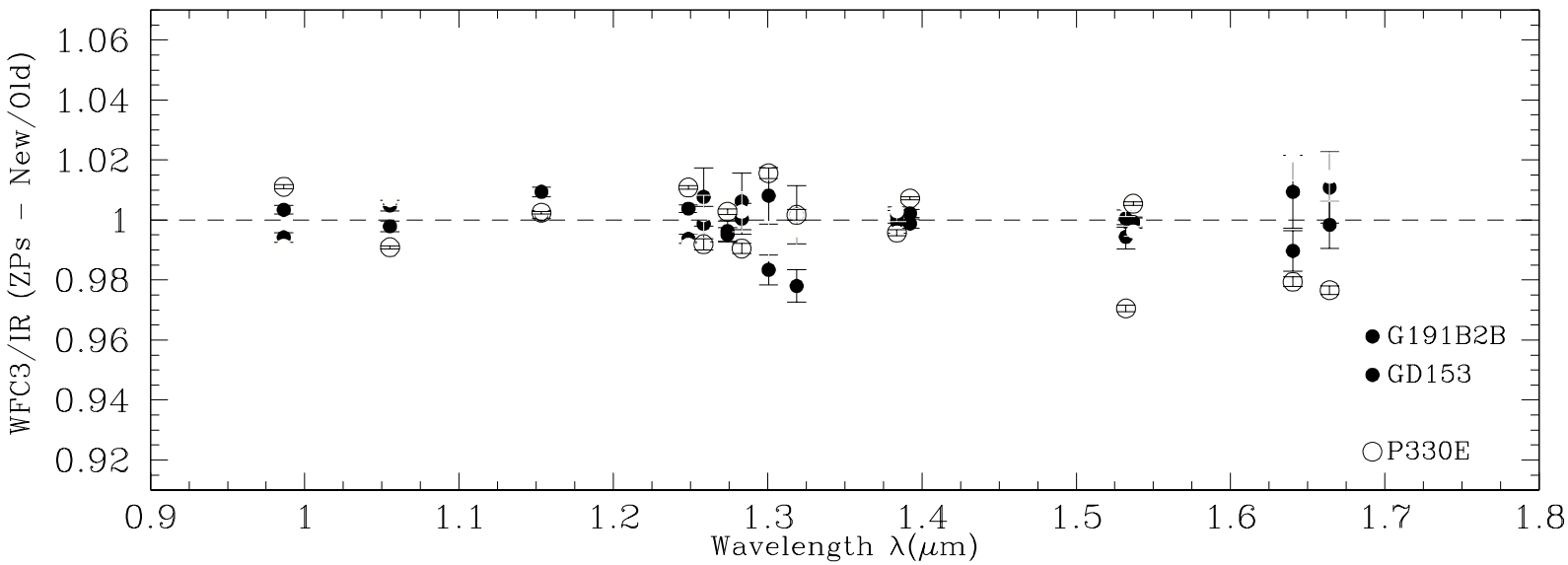
2012


WFC3/UVIS (ZPs – New/Old)
1.16
1.12
1.08
1.04
1
0.96
0.92
0.88
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Wavelength λ(μm)
G191B2B
GD153
GD71
P330E

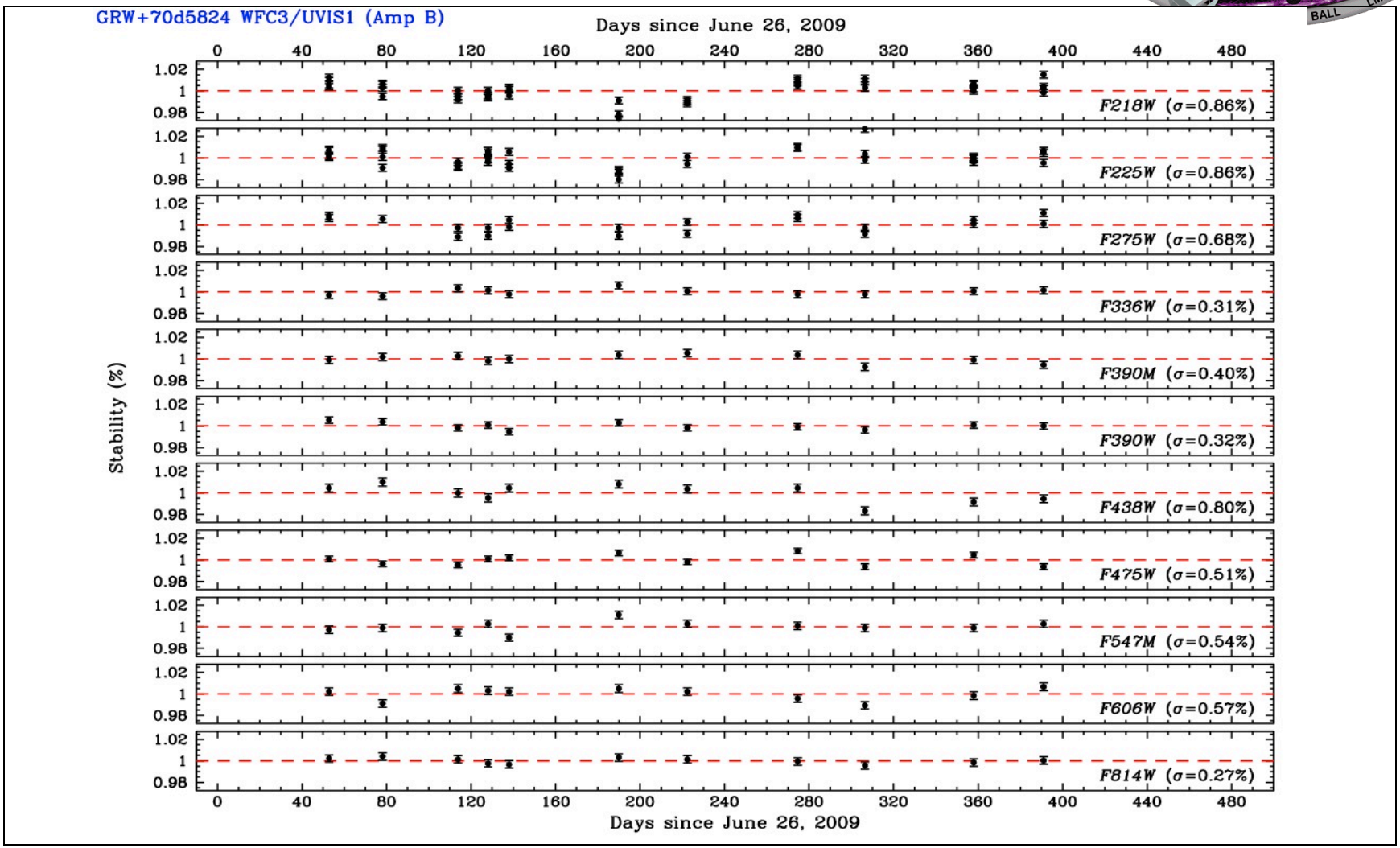

WFC3/IR (ZPs – New/Old)
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Wavelength λ(μm)
G191B2B
GD153
GD71
P330E

2012- ETC

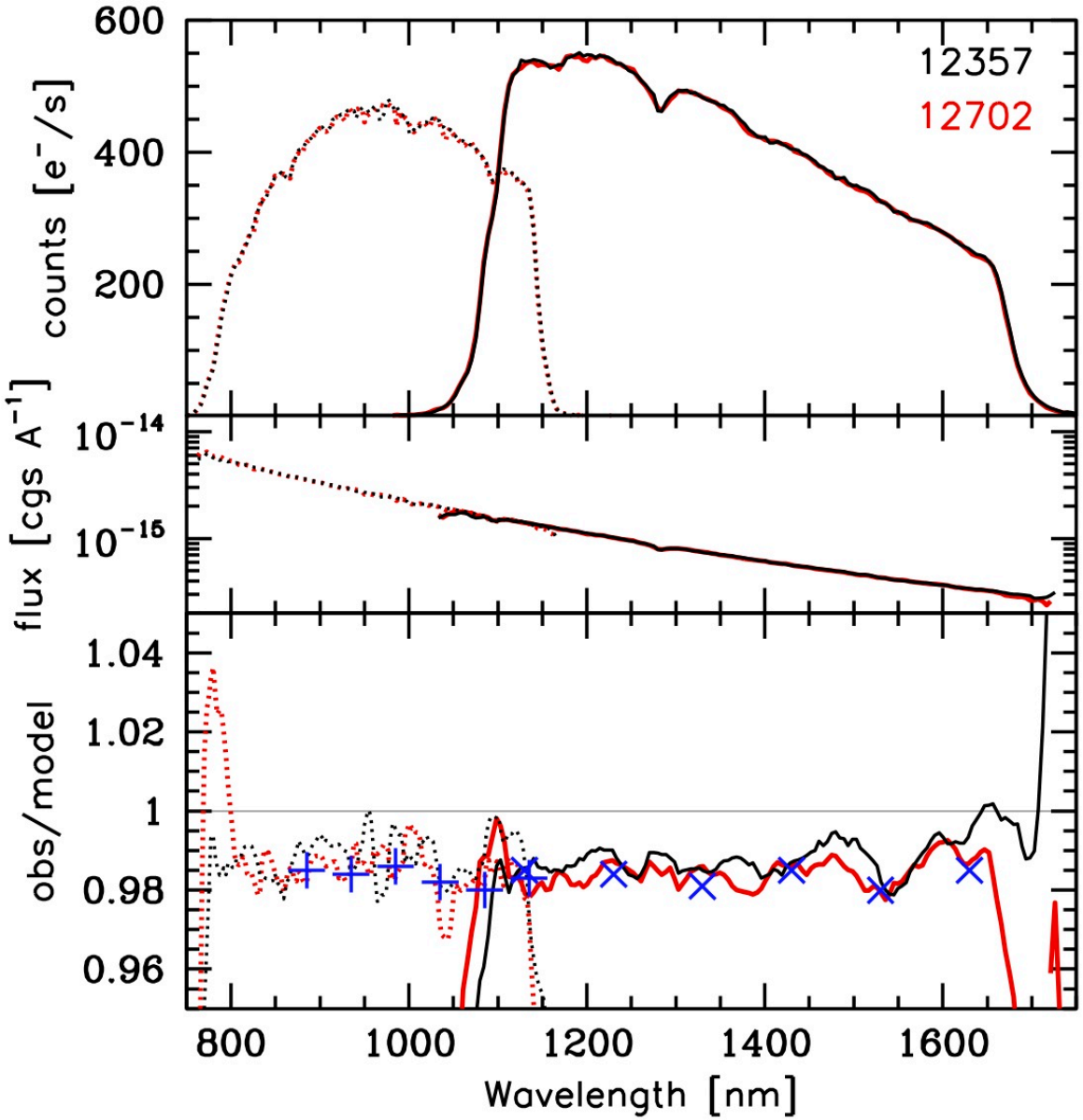

WFC3/UVIS (ZPs – New/Old)
1.16
1.12
1.08
1.04
1
0.96
0.92
0.88
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Wavelength λ(μm)
G191B2B
GD153
P330E


WFC3/IR (ZPs – New/Old)
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Wavelength λ(μm)
G191B2B
GD153
P330E

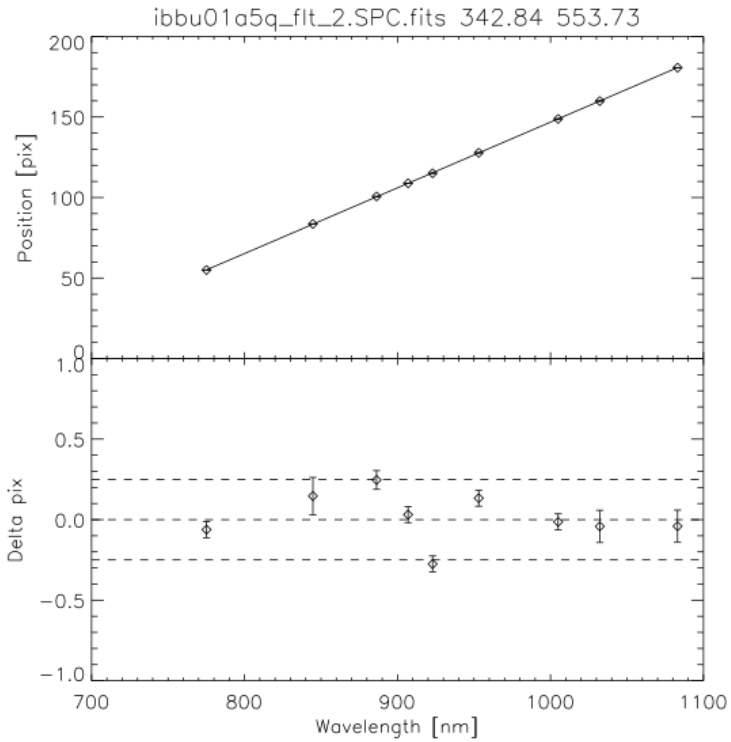
Photometric Stability ~0.5%

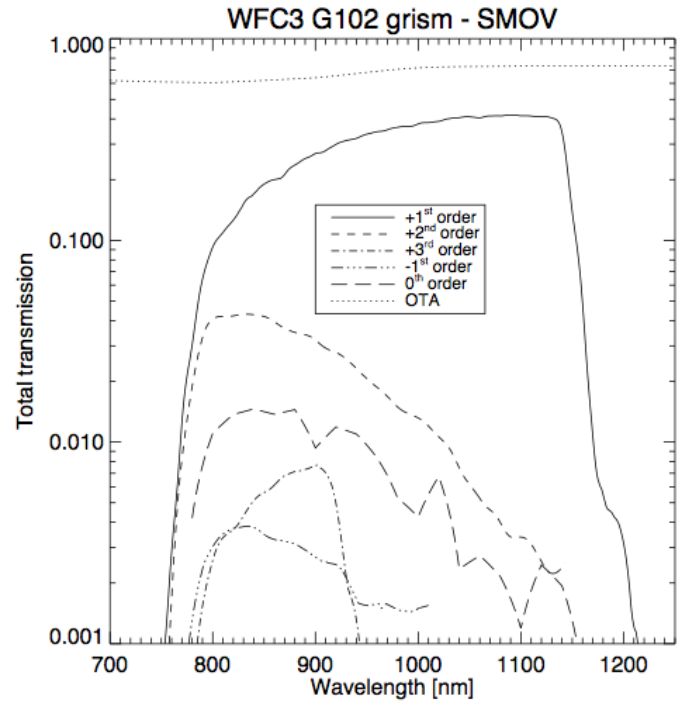


WFC3/IR Grism Flux Calibration Stability: G141



G102 Grism


ibbu01a5q_flt_2.SPC.fits 342.84 553.73
Position [pix]
Delta pix
Wavelength [nm]


WFC3 G102 grism - SMOV
Total transmission
Wavelength [nm]
+1st order
+2nd order
+3rd order
-1st order
0th order
OTA

WFC3 Photometric Calibration and Calibration Flux Ladder

Objective:

Improve the absolute photometric calibration and cross-calibration of user grism and imaging observing modes

Minimize uncertainties due to models, drive absolute calibration to <0.5%.

Description of the observations:

Direct images of 4 CALSPEC standards (UVIS & IR) & V>14 mag

Spatial scans 9< V < 13 mag stars: IR grism and imaging

Targets: STIS, ACS, NICMOS, SPITZER/IRAC, and JWST standards.

P330E, VB8, GD71 and GD153

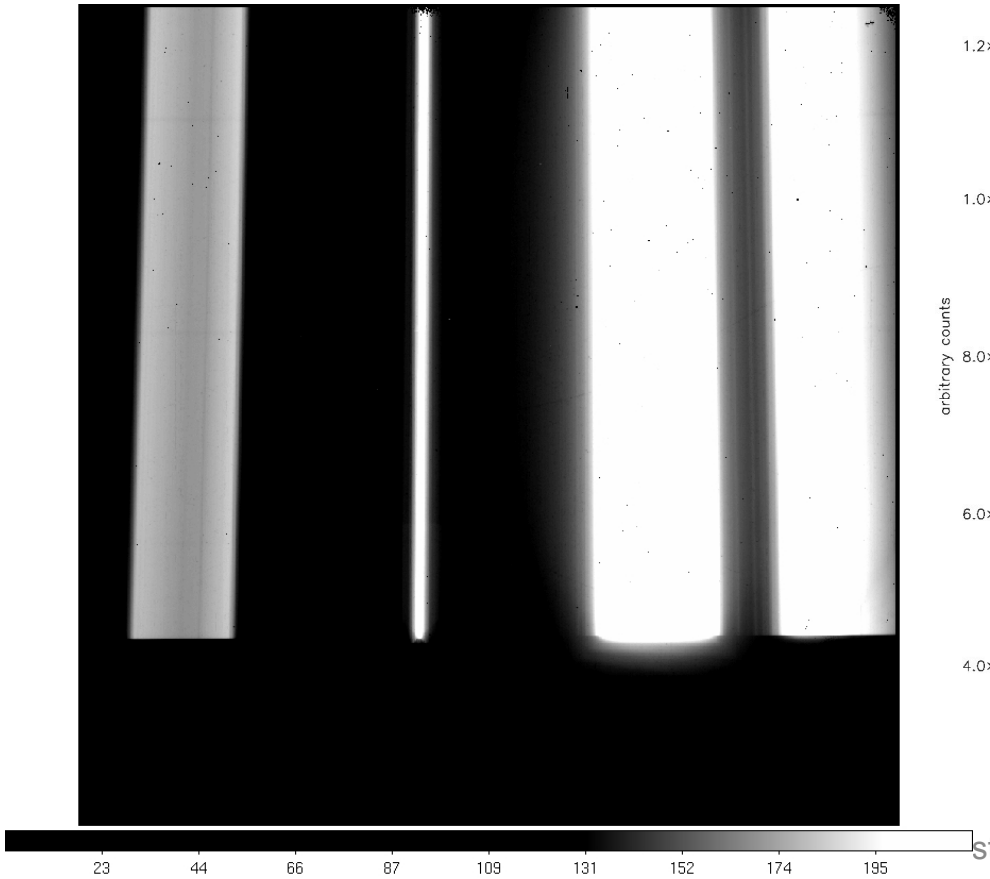
A-type stars: HD165459 (A4V), 1732526 (A4V), 1740346 (A6V), 1743045 (A8II), 18032271 (A2V), 1805292 (A4V), 1812095 (A5V)

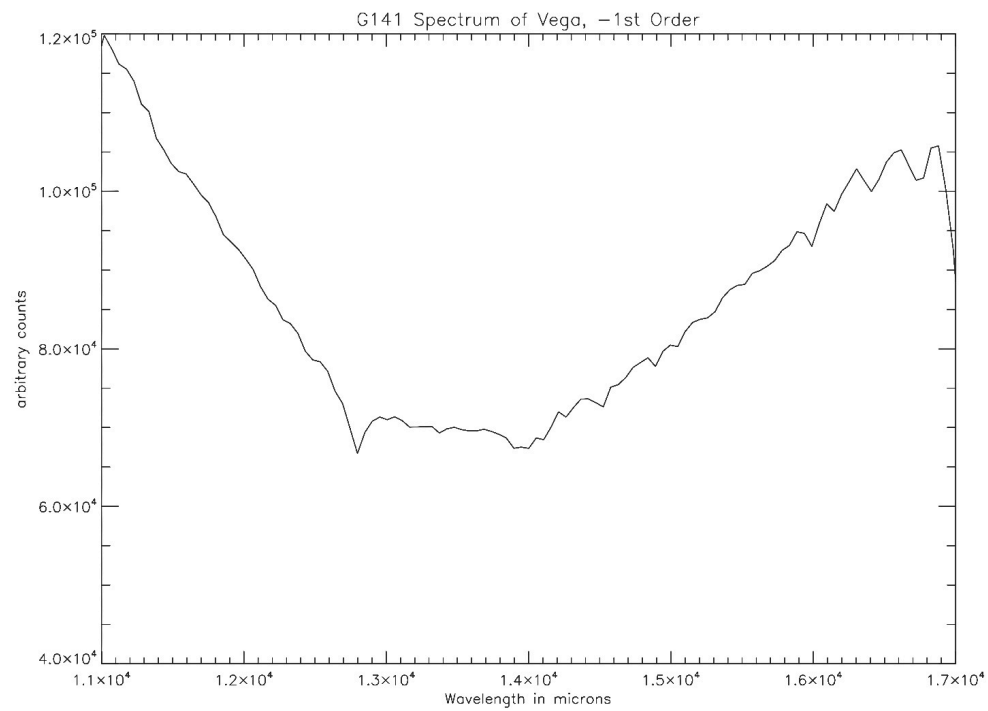
G-type stars: HD209458 (G0V), P041C (G0V), P177D, SNAP-2 (GO-5)

Other: 2M0036+18 (L3.5), 2M0559-14 (T5), KF06T2 (K1.5III)

Vega in the G141 Grism

- Scanned spectra of Vega with both IR grisms.
- Vega placed in 3 positions on the array
- Scan rate = ~5 arcsec/sec and 7 arcsec/sec.





Lessons learned

- Expect change
- No atmosphere in space – good
- Radiation, shake 'n bake – not so much
- Illumination corrections are doable in orbit for imaging
- Stray light is insidious
- Some basic calibration hardware is essential
  - Even IR detectors need a mechanical shutter for darks
- Innovation is essential

(especially when NASA SMD Associate Administrator John Grunsfeld can't get to orbit and add hardware)

The WFC3 Scientific Oversight Committee

- Bruce Balick, University of Washington
- Howard E. Bond, Space Telescope Science Institute
- Daniela Calzetti, Space Telescope Science Institute
- C. Marcella Carollo, Institute of Astronomy, ETH, Zurich
- Michael J. Disney, Cardiff University
- Michael A. Dopita, Mt Stromlo and Siding Spring Observatories
- Jay Frogel, AURA
- Donald N. B. Hall, University of Hawaii
- Jon A. Holtzman, New Mexico State University
- Randy Kimble, NASA Goddard Space Flight Center (ex officio)
- Gerard Luppino, University of Hawaii
- Patrick J. McCarthy, Carnegie Observatories
- John MacKenty, Space Telescope Science Institute (ex officio)
- Robert W. O'Connell, University of Virginia (Chair)
- Francesco Paresce, European Southern Observatory
- Abhijit Saha, National Optical Astronomy Observatory
- Joseph I. Silk, Oxford University
- John T. Trauger, Jet Propulsion Laboratory
- Alistair R. Walker, Cerro Tololo Interamerican Observatory
- Bradley C. Whitmore, Space Telescope Science Institute
- Rogier A. Windhorst, Arizona State University
- Erick T. Young, University of Arizona

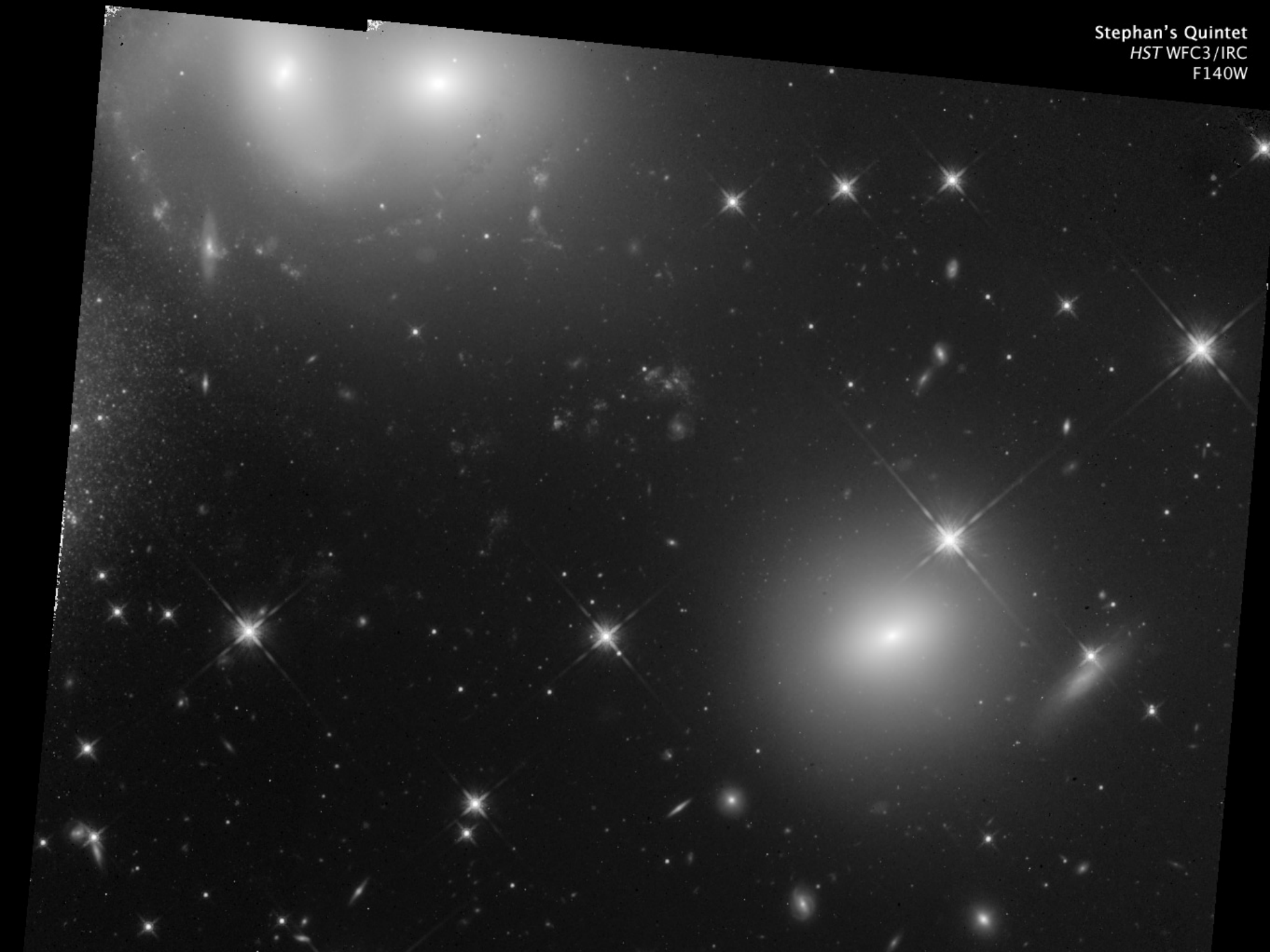
Past WFC3 Team

Wayne Baggett
Howard Bond
Howard Bushouse
Tom Brown
Laura Cawley
Ed Cheng
Ilana Dashevsky
Don Figer
Mauro Giavalisco
Shireen Gonzaga
Christopher Hanley
George Hartig
Ron Henry
Jason Kalirai
Jessica Kim Quijano

Randy Kimble
Pat Knezek
Ray Kutina
Casey Lisse
Olivia Lupie
André Martel
Brian McLean
Abhijith Rajan
Neill Reid
Massimo Robberto
Michael Robinson
Megan Sosey
Massimo Stiavelli
Michael Wong

- **WFC3 Management, Engineering, and Contractor Teams**
- Thai Pham and Jackie Townsend, GSFC Instrument Managers
- GSFC Engineering Teams in Codes 400, 500, and 600 (plus Code 300 reviewers)
- Ball Aerospace, Swales Aerospace (now ATK), Teledyne, E2V, and many others

300-400 people made significant contributions to the development of Wide Field Camera 3


Stephan's Quintet
HST WFC3/IRC
F140W