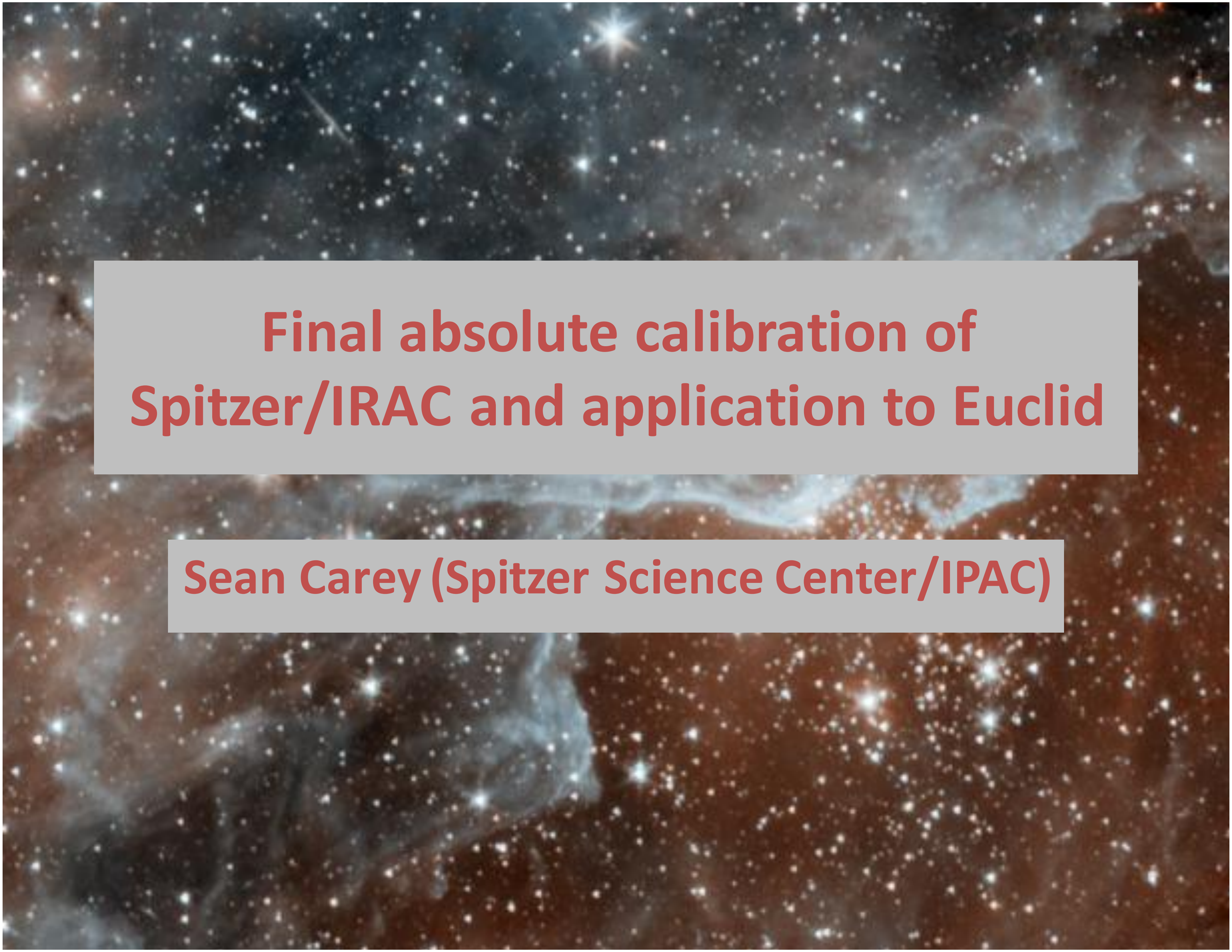


Final absolute calibration of Spitzer/IRAC and application to Euclid

Sean Carey (Spitzer Science Center/IPAC)

Calibration Requirements

Photometric accuracy: 10% absolute, 2% relative (p-p)

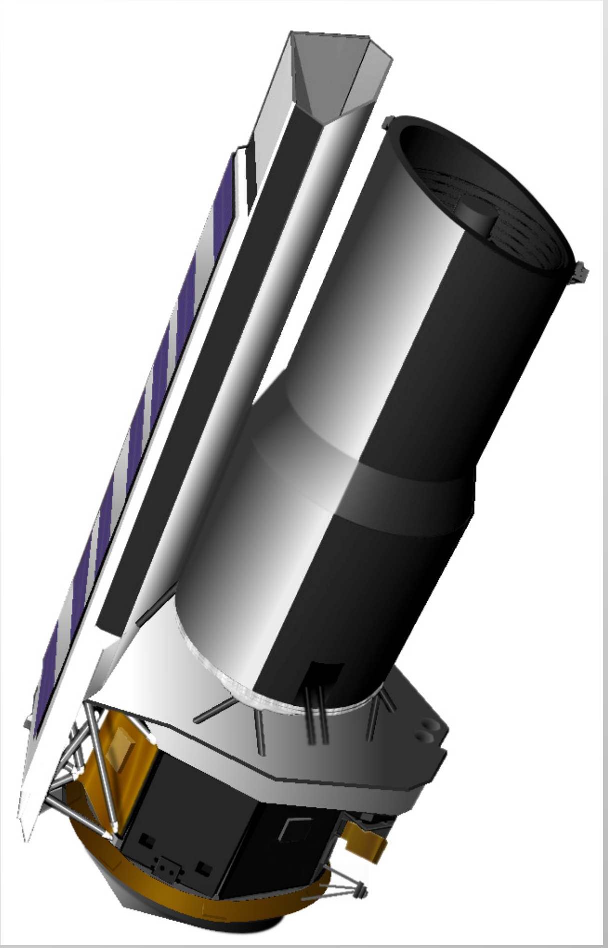
Breakdown of 2% relative error:

- Instrumental variations and requirements
  - Responsivity stability - ±0.5% p-p over one hour, ±1% over 12 hours
  - Instrumental polarization characterized to 1% accuracy, to meet photometric requirement for sources up to 40% polarization
  - Out-of-bandpass blocking such that the total flux is less than 0.2% of in-band total, for sources of arbitrary temperature
  - Measurement requirements
  - Pixel-to-pixel gain variations - after corrections, must be <1% error between two measurements over a 12 hr period
  - Astronomical flux standards - primary and secondary
  - Errors in measurements and extraction

Courtesy of Joe Hora (SAO/CfA)

Spitzer Review

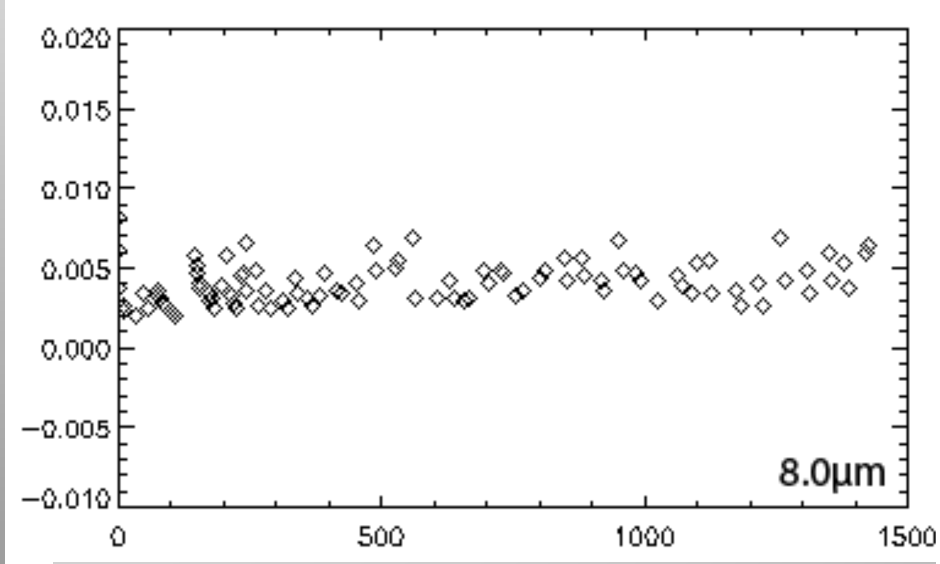
- Launched 25 August 2003
- 0.85m f/12 beryllium primary
  - Diffraction limited at 5 μm
- Three science instruments
  - InfraRed Array Camera (IRAC) : mid-IR camera
  - Infrared Spectrometer (IRS): mid-IR spectrometry
  - MIPS: mid to far-IR imager/spectrometer
- Earth-trailing orbit
  - Currently more than 1.5 AU away
- Passive cooling to < 30K
  - Active cooling of primary down to 5.5 K
- Cryogen exhausted May 2009 (>5 yr lifetime)



Basics of IRAC

- 4 arrays: 2 fields of view (3.6/5.8 μm), (4.5/8.0 μm)
  - 256 × 256 InSb and Si:As arrays
  - 1.22 arcsecond pixels (30 μm)
  - InSb arrays are undersampled
- Sensitive but able to map large areas
  - 5 arcmin FOV
  - <1 e^-/s dark current
  - <20 e^- of read noise (Fowler-2)
  - 1-10 μJy sensitivity in 100s
  - 400 hrs to map 220 sq degrees of Galactic plane
- Exceptionally stable
  - **Thermally controlled to ~ 3mK**
  - Gain maps to < 0.4%
  - Photometry repeatable to < 1%

Average fractional uncertainty vs. time for individual flat-field



Days since initial power on

Calibration Methodology I

- Calibration factor (DN/s to Jy) determined by comparison of measurements to calibrated spectral templates

$$C = \overline{\left(\frac{F * K *}{DN_{obs} / t_{\exp}} \right)}$$

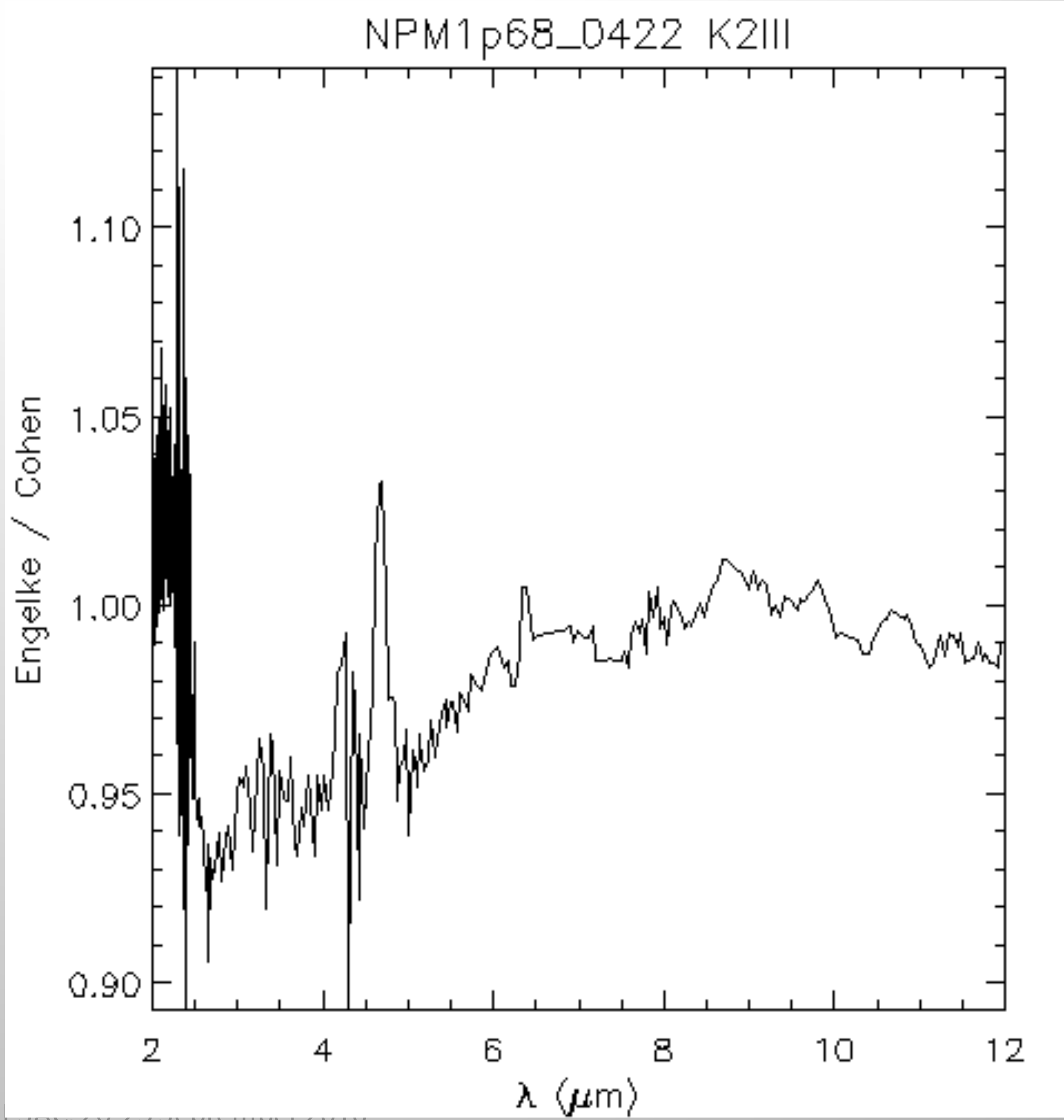
- F^* = Flux density @ effective wavelength
- K^* = Color correction assuming reference $F_\nu = F_{\nu 0} \times (\nu/\nu_0)^{-1}$
- Primary calibrators used
  - 4 A0V templates (Kurucz models + photometry; Cohen et al. 2003)
  - 5 K0-K2III templates (ISOSWS reduction + photometry from Engelke et al. 2006
  - Earliest calibration just used A0V stars
- A0V templates use Vega model, KIII templates use Sirius/109 Vir template

Calibration Methodology II

- Photometry referenced to standard aperture of 10 pixels with 12-20 pixel background annulus
- Centroids determined using 1st moment of light in a 7x7 pixel box around peak pixel
- 3 pixel radius aperture with 3-7 pixel background annulus used for actual measurements
  - aper.pro from IDL astrolib used
- Need dedicated calibration campaigns as science observations do not guarantee calibration quality data
  - IRAC science consists of a heterogeneous set of General Observer programs
  - 4% of time is being used for instrument calibration including 70 minutes/week for calibration star observations

IRAC AV / KIII Calibration Offset

- In Reach et al. (2005) difference between Predicted/Observed between AV and KIII calibrators was **7.3%**, **6.5%**, **3.6%** and **2.1%** for 3.6, 4.5, 5.8 and 8.0 µm
- Improved reduction of ISO spectra produced better templates

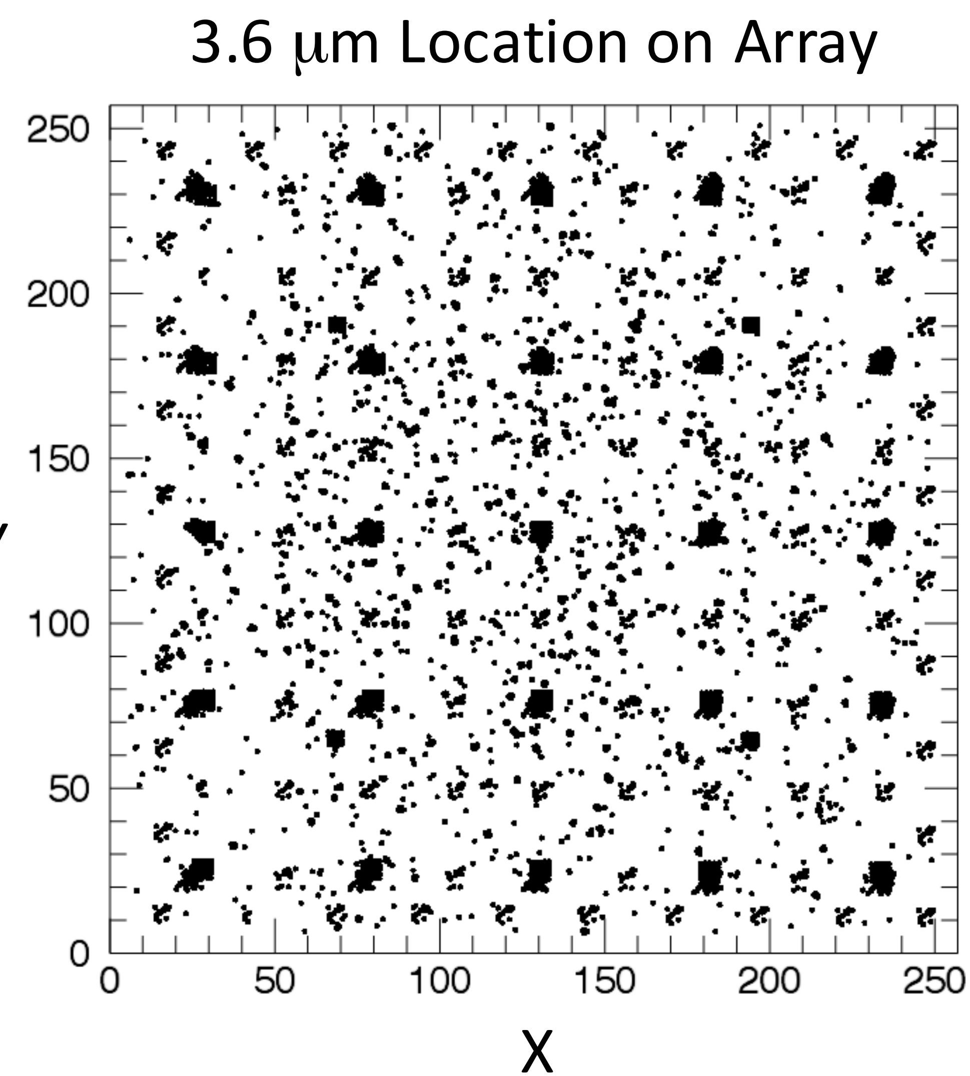


Photometric Systematics and Absolute Calibration

- Use calibrators to solve for systematic variations
  - Array-wide
  - Intrapixel
- Solve both variations simultaneously with per-star flux conversion factor
- Correct photometry for systematics, then re-solve primary calibrator network for flux conversion factor
- Assume that measurement errors per star goes as $N_{obs}^{-0.5}$, $N_{obs} > 500$: this error effectively disappears
- Assume that error in flux conversion goes as $N_{star}^{-0.5}$, $N_{star} = 4,5$ so we get factor of two
- Average over calibrator types to reduce systematic bias

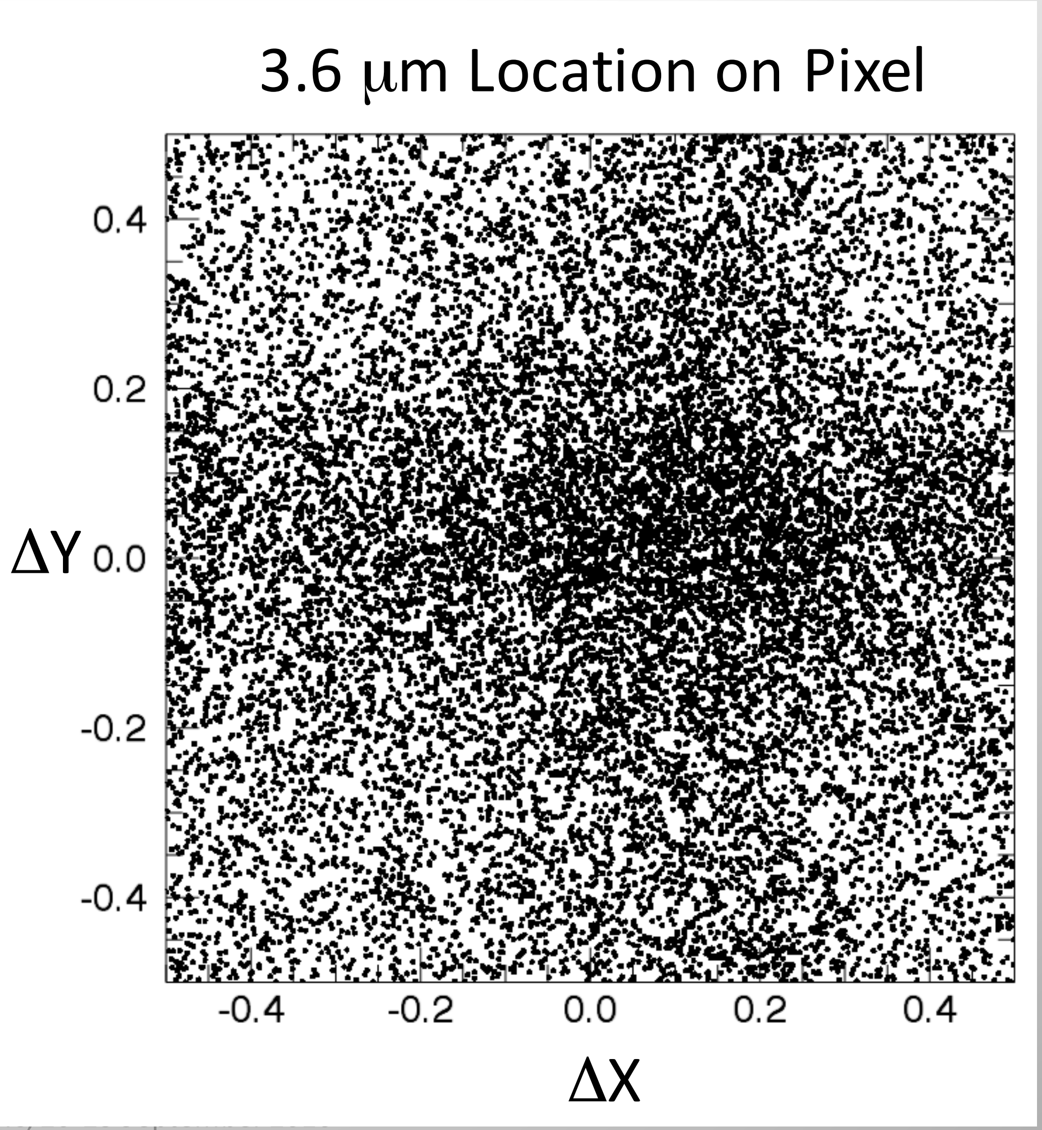
Mapping the Arrays

- Regular grid across array
- High density sampling for PRF
- Sparse random sampling to check for higher frequency structure
- Multiple phases on many pixels

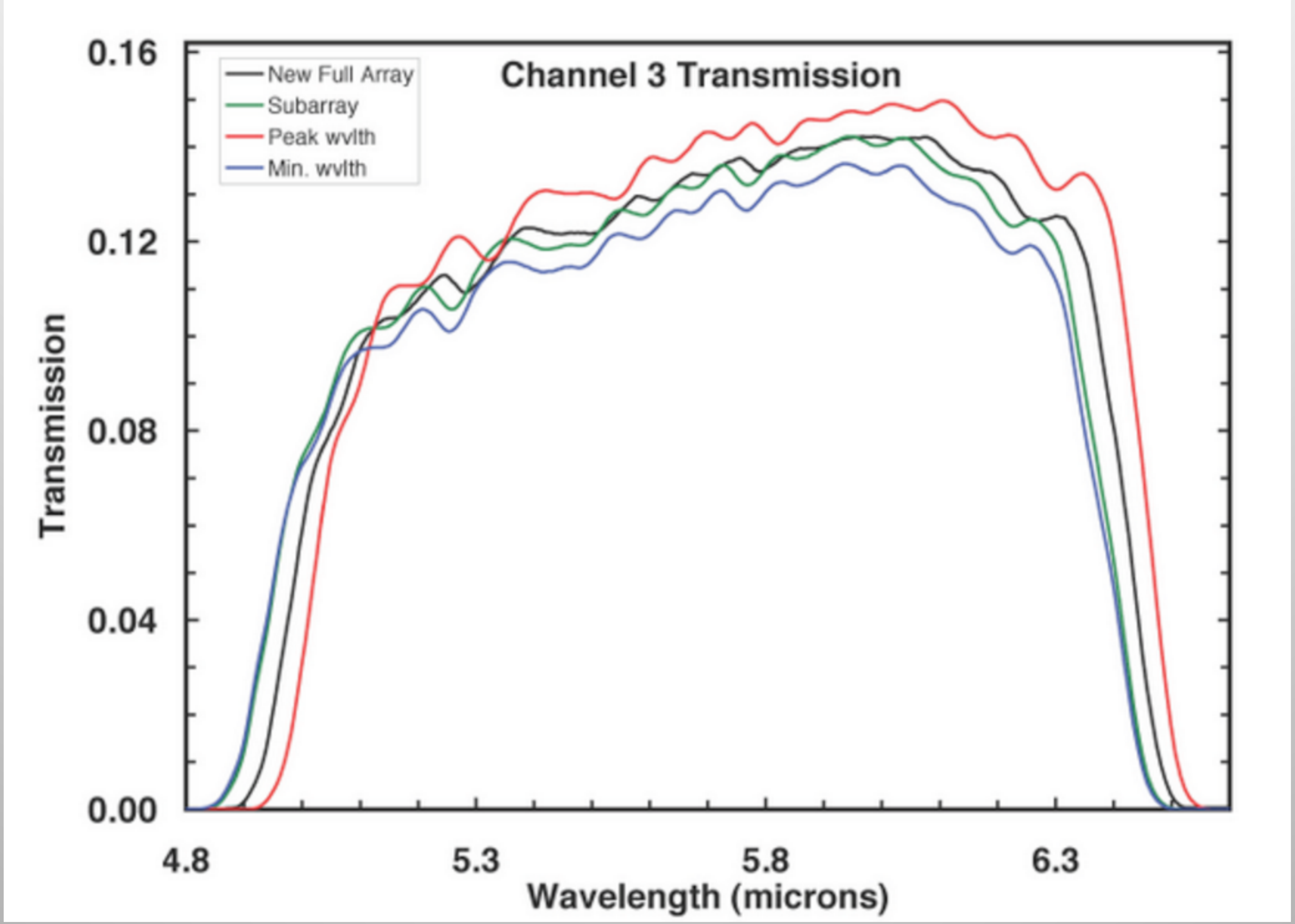


Mapping the Arrays

- Regular grid across array
- High density sampling for PRF
- Sparse random sampling to check for higher frequency structure
- Multiple phases on many pixels

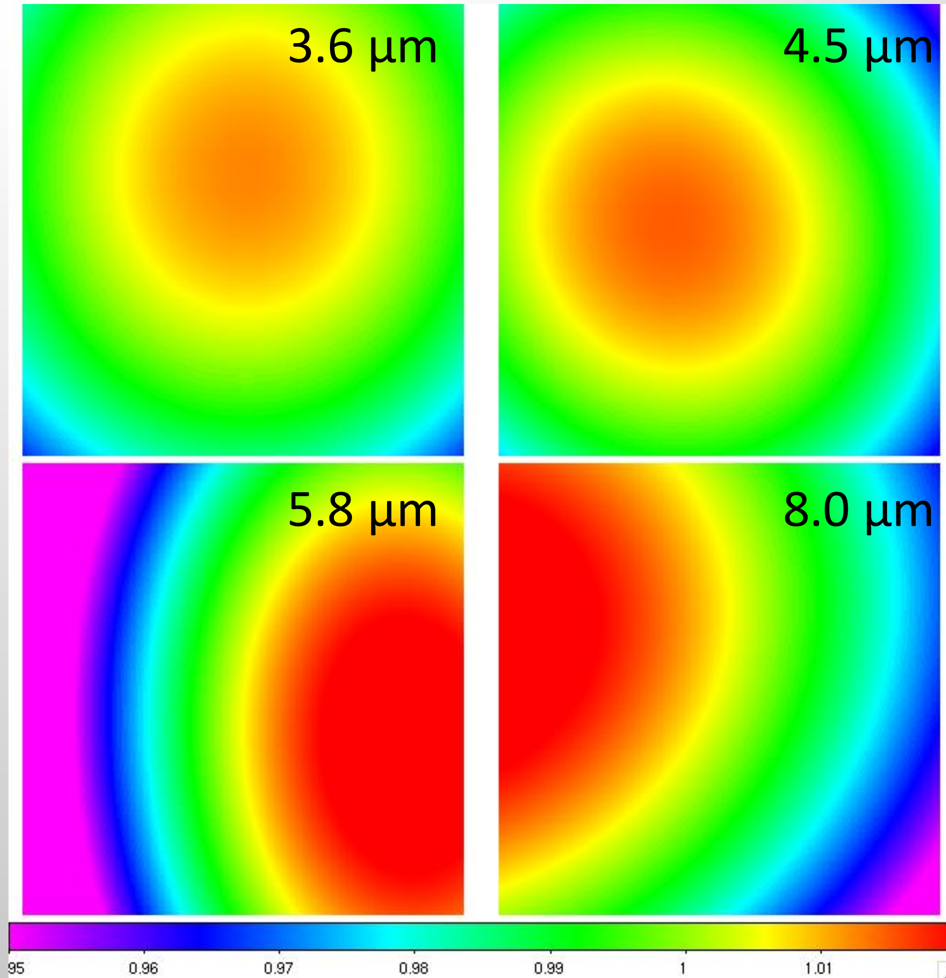


Filter Profile Changes Effect Photometry



Array Location Dependent Correction

- Photometry varies due to change in filter bandpass as light is incident with different angles (paths) through filter
- 30° variation in angle for 5 arcmin FOV
- 10% effect across array
- Change in pixel solid angle ~1% effect
- Photometric variation for stars (R-J sources in IRAC bandpasses) is amplified due to use of Zodiacal light as flat-field

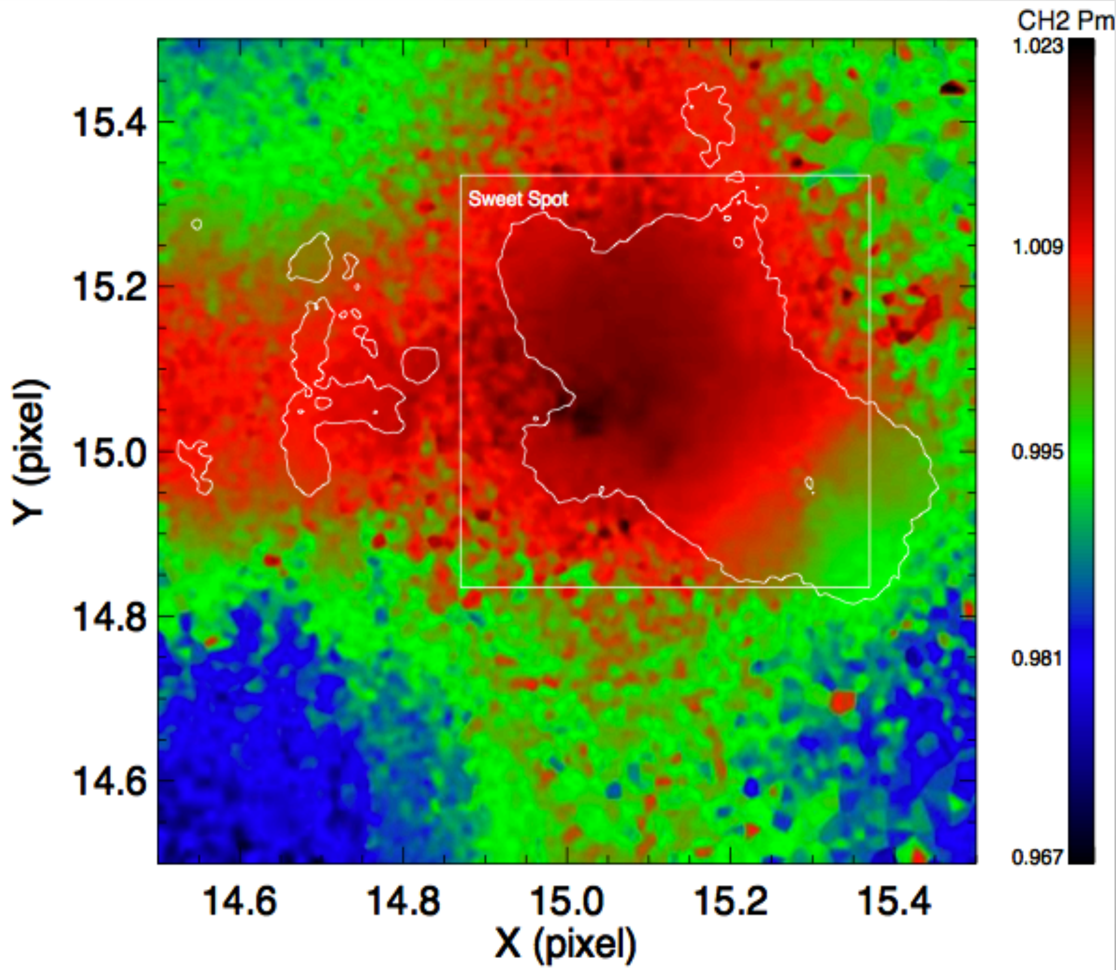


Modeled as a 2nd order polynomial in x and y

Intrapixel Photometric Variation

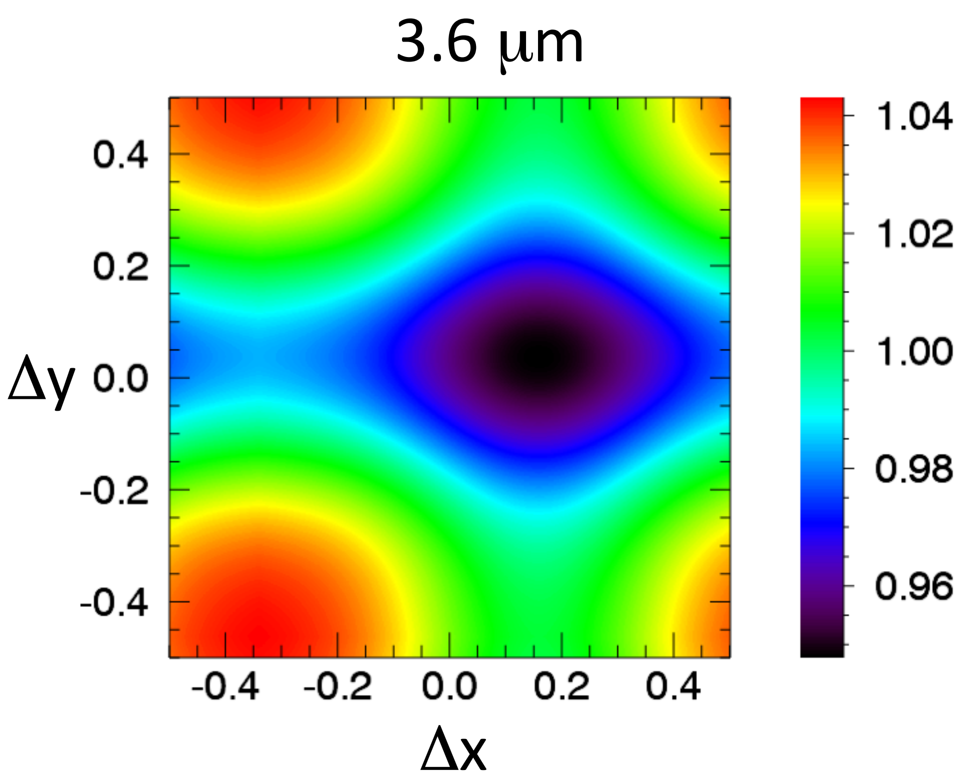
- Observed flux of source on InSb arrays depends on position relative to pixel center
- Function of variation in pixel gain and undersampling of PSF
  - 4% and <1% effect in cryogenic mission
  - 7% and 4% effect in warm mission
- Trending of intrapixel variation is limiting factor in exoplanet light curve precision
  - Best current precisions are 30-50 ppm

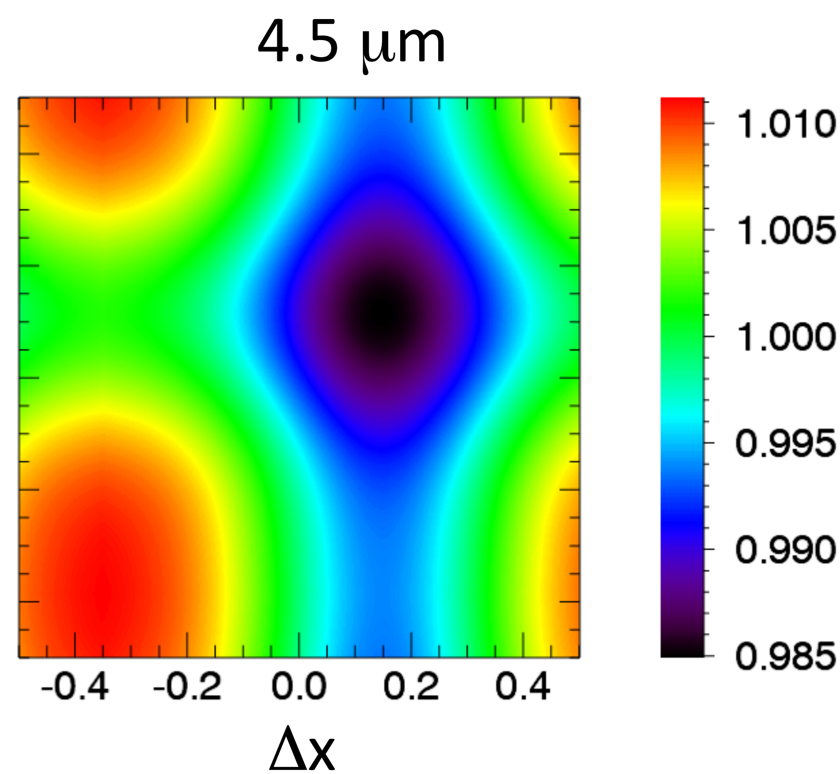
4.5 μm



High-precision map of a single pixel used for exoplanet observations

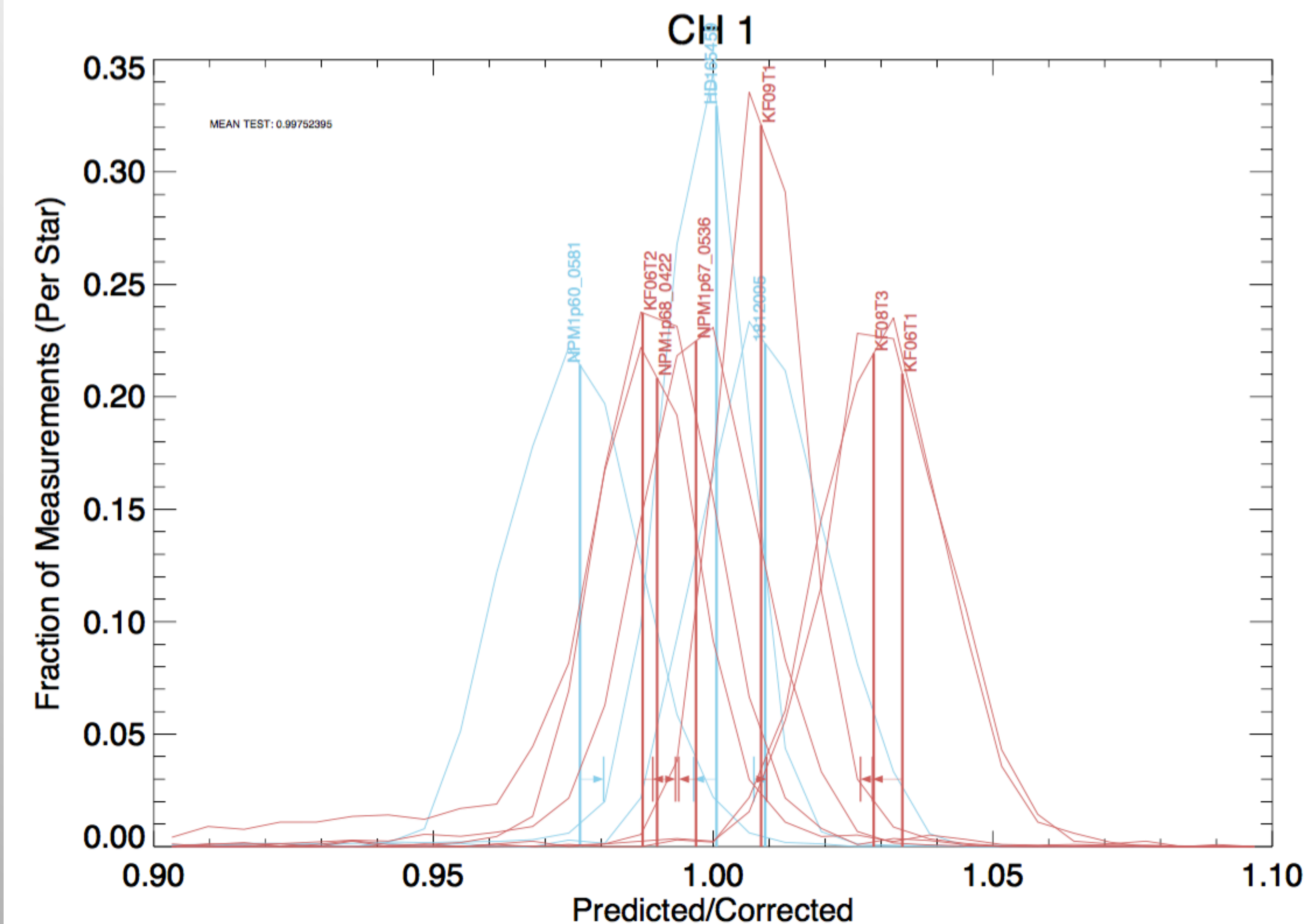
Warm IRAC Intrapixel Response Models



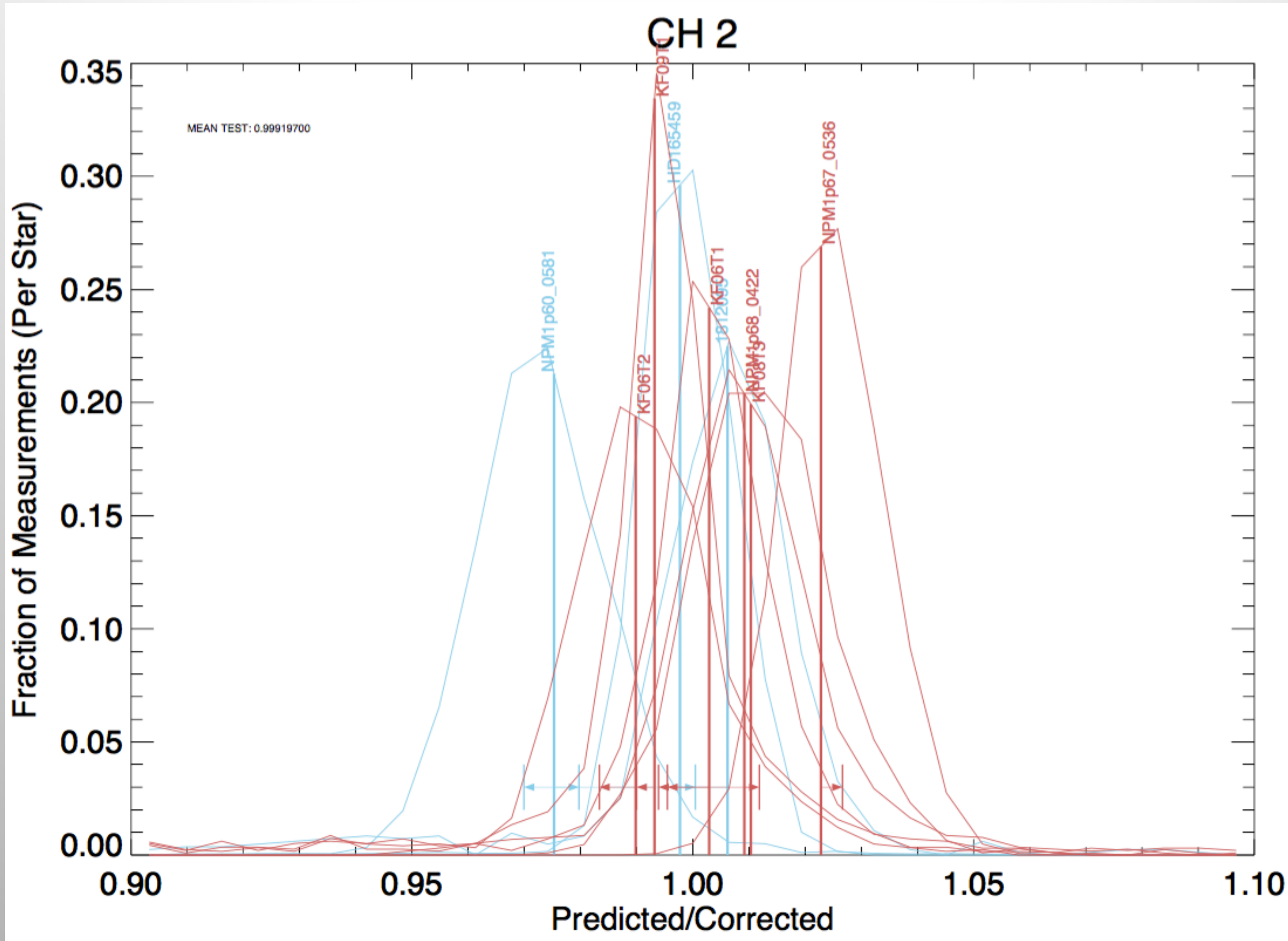


- Two-dimensional Gaussian pixel-phase functions

3.6 μm Predicted vs. Measured Warm Data



4.5 μm Predicted vs. Measured Warm Data



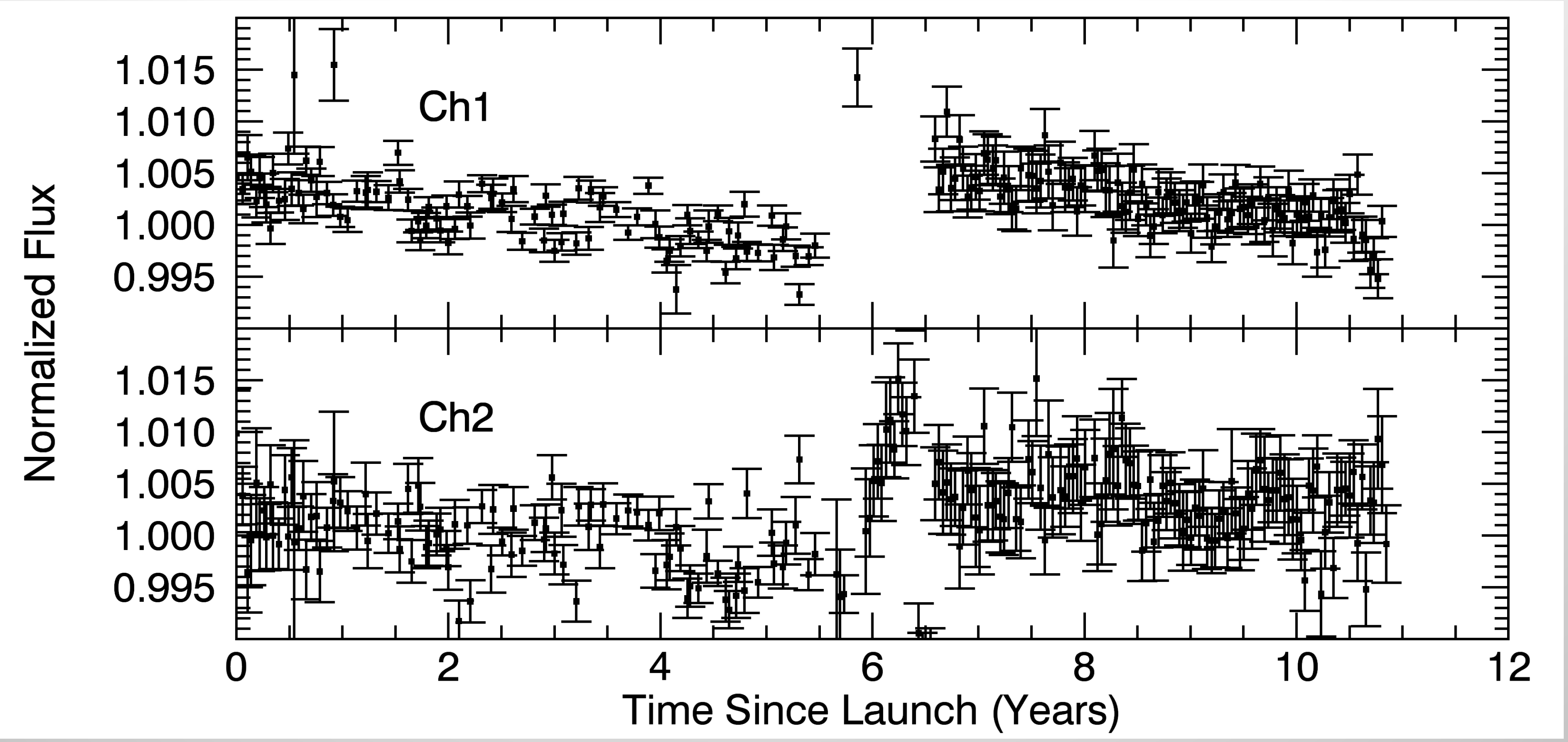
Accuracy of Cryogenic Photometric Calibration

Band	σ_m	σ_{zero}	A-K bias	Calspec bias
3.6	0.6%	1.5%	-1.79%	0.4%
4.5	0.5%	1.5%	-1.25%	-0.3%
5.8	0.6%	1.5%	0.48%	-3.9% (-0.3%)
8.0	0.6%	1.5%	-1.39%	-1.2% (-0.7%)

σ_m: measurement uncertainty
σ_{zero}: assumed Vega uncertainty
A-K < 0 implies K star derived cal factor is lower
(): Calspec bias without WD measurements

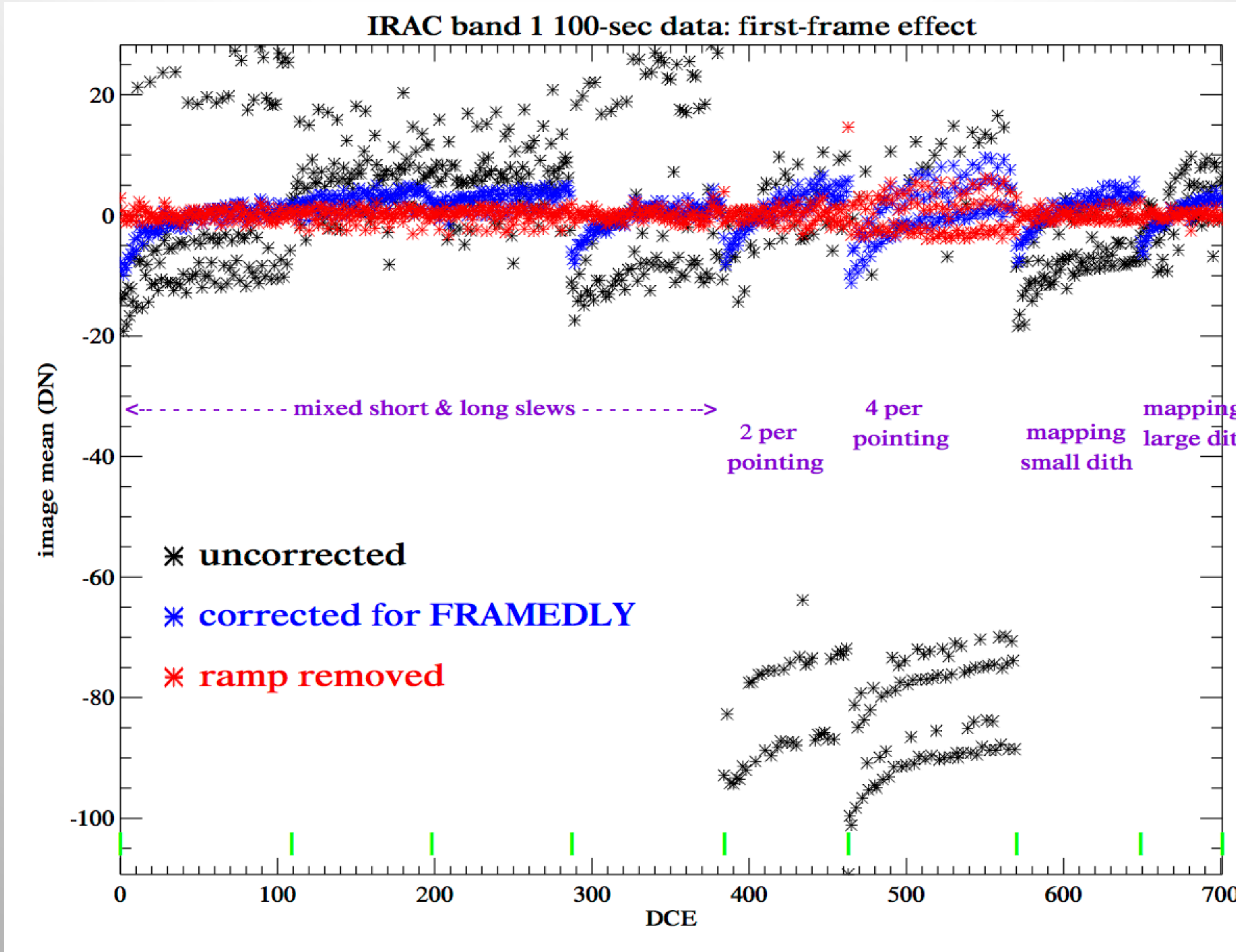
- A/K discrepancy larger than uncertainty of average
- Calspec (HST) bias = measured - predict
  - WD measurements at 5.8 & 8.0 μm are problematic
- Differences between different calibration schemes at limit of their uncertainties
  - Systematics in zero point/fundamental calibration not well understood
- Warm accuracies are similar and dominated by A-K bias

Photometric Stability



- Mean of normalized flux for calibrators during a campaign
- ~0.1% per year at 3.6 μm, apparent trend at 4.5 μm
- Not a change in detector properties as slope is same after bias change
- Radiation damage in transmissive optics creating more scattering

History Dependent Bias Variations

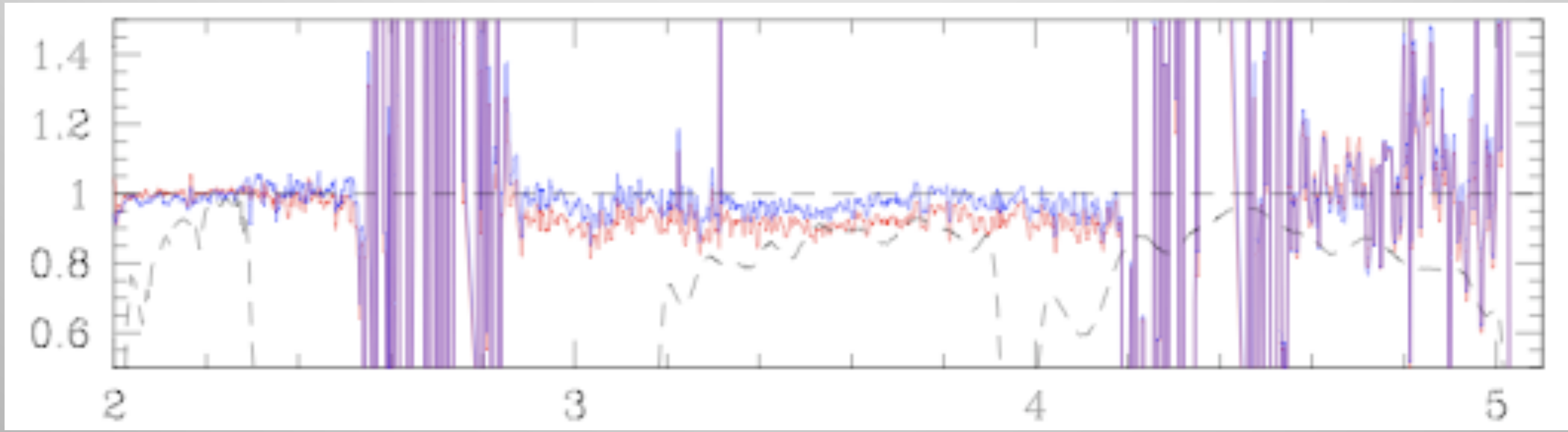


Summary

- Photometric calibration of IRAC is better than 2%
- Transfer to physical units largest uncertainty
- Use of multiple calibrator types reduces systematic bias
- Photometric systematics can be reliably trended using ensemble of data
- Trending in time may produce interesting results

Engelke / Cohen Comparison

- IRTF SpecX data of NPM1p68.0422 (K2III) calibrator for IRAC
- Red is ratio of spectra / Cohen template
- Blue is ratio of spectra / Engelke template



μm