Space-Based Imaging Astrometry: Life with an Undersampled PSF

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Overview of the Talk

- **Astrometry with HST**
  - 3 critical issues
  - Science
    - General
    - Microlensing
- **Extensions to WFIRST**

Astrometry with HST

- **One of the original selling points**
  - FGS: always planned
  - Also intended imaging astrometry

- **Several challenges**
  1) Undersampling → PSFs
  2) Distortion (several sources)
  3) Differential astrometry → Transformations

     …. took several years to address these issues.

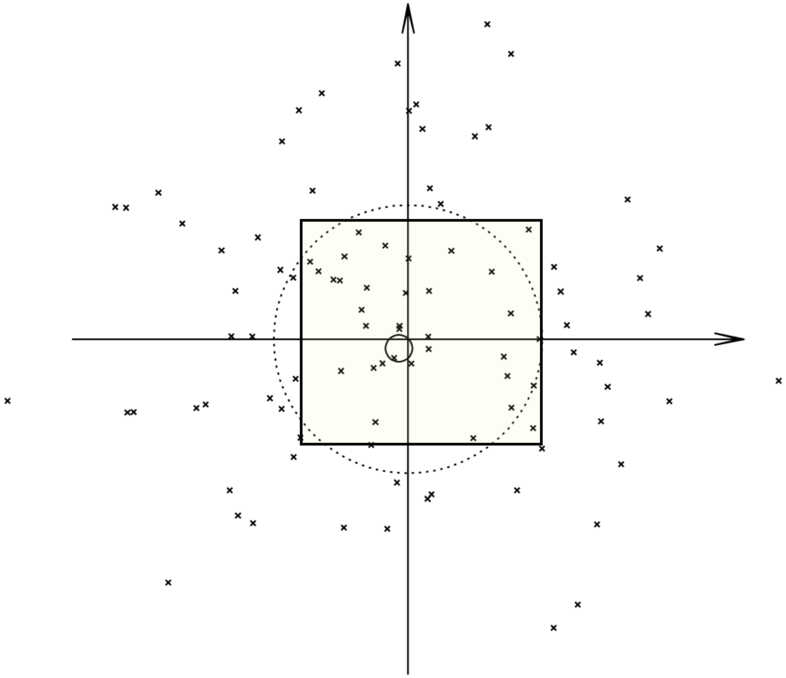
Goal of talk: an appreciation of the issues and possibilities

Astrometry:

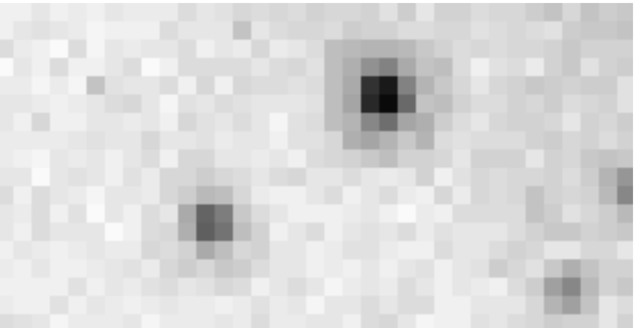
Fundamental limitations

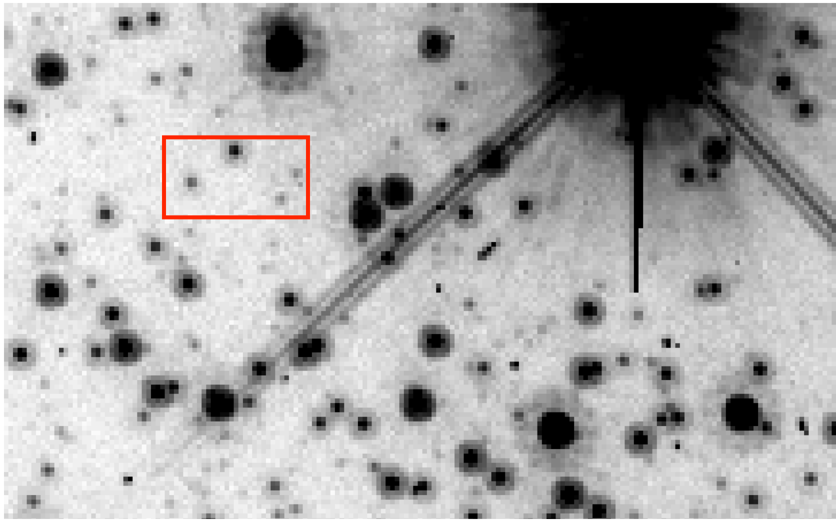
- **Poisson statistics**
  - Gaussian PSF

    $\delta x \sim \sigma_x / \sqrt{N}$
  - Best position: straight centroid



- **Pixelization**
  - Complication: loses information
  - Simple centroid no longer works
  - Requires good PSF

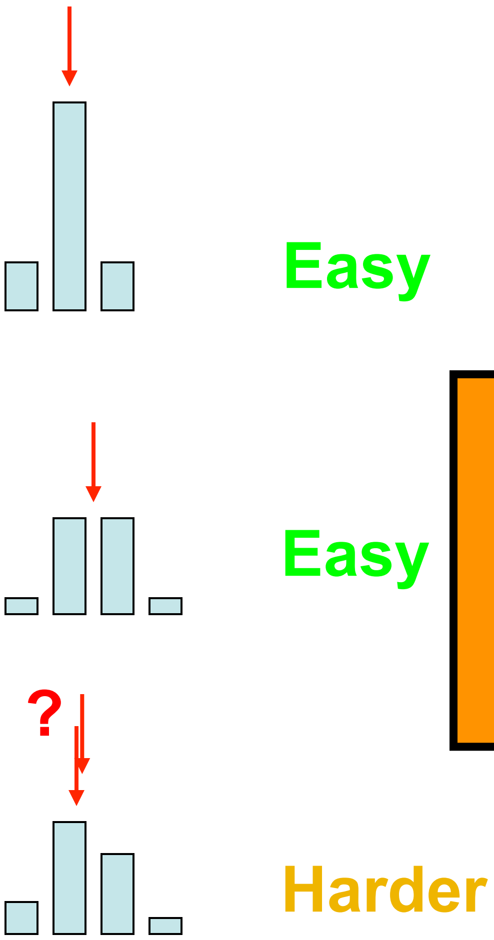




WFC3/UVIS SWEEPS FIELD

Illustration of Undersampling

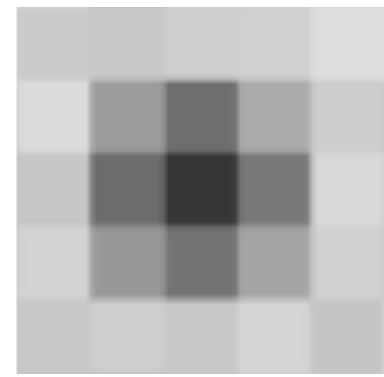
Where is the center?



We need an accurate PSF!

Undersampling and Astrometry

- **Impossible?**
  - A point source has “no hair”
  - Overconstrained problem
    - 3 parameters (x,y,f), ~9 pixels
  - Minimal requirements: “slosh”
    - Only pathological if FWHM < 1 pixel
- **What is possible?**
  - 0.005-0.01 pixel possible ~ $(S/N)^{-1}$
  - Need good PSF model
  - Need good dithering
- **Limitations**
  - Individual images; do **not** use stacks
  - Harder in crowded/sparse fields
  - Ideal in “semi-crowded” regime



PSFs: Photometry -vs- Astrometry

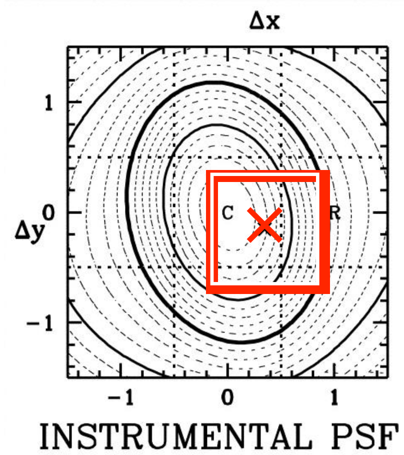
- **Photometry: how much flux is there? (SUMS)**
- **Astrometry: where is the flux? (DIFFERENCES)**
- **Shape: *exactly* where is flux… (DIFFs of DIFFs)**
  - All require good PSF, but they make different demands
- **PSF Modeling**
  - Ground
    - Variable-seeing dominated
    - Gaussian-fitting models, DAOPhot
  - HST
    - Stable but undersampled, new regime
    - Exquisitely precise models possible

What do we mean by the PSF?

- **$\psi_{INST}(\Delta x,\Delta y)$: the "Instrumental" PSF:**
  - The PSF as it hits the detector
  - Good theoretical motivations: Gaussians, Moffat
  - See ψ_{INST} only *indirectly* in images
    - Must deconvolve the PSF from the pixels
    - Saving grace: often solve for limited set of parameters

- **$\psi_{EFF}(\Delta x,\Delta y)$: the "Effective" PSF:**
  - The PSF after pixelization: $\psi_{EFF} = \psi_{INST} \otimes \Pi$
  - Empirical: no natural basis function to describe
  - Tod Lauer's 1999 tutorial in PASP on image reconstruction
    - **OLD:** Pixels as light buckets
    - **NEW:** Pixels as point-samplings of a continuous scene
  - **Epiphany**: we *never* deal with anything BUT the effective PSF
    - See ψ_{EFF} *directly* in images
    - Can measure ψ_{EFF} directly from images

The "Effective" PSF



- **What it represents:**
  - Fraction of light that falls in a pixel, relative to the center of the star
- **Modeling images:**

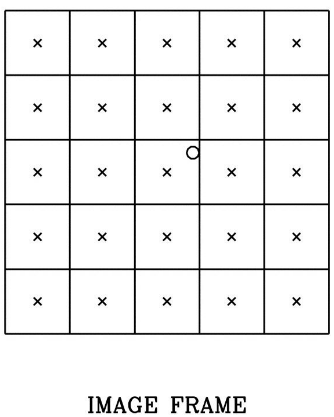
OLD: $P_{ij} = S + F_* \times \int\int_{x,y\in(i,j)} \psi_{INST}(x-x_*,y-y_*)\, dx\, dy$

NEW: $\boxed{P_{ij} = S + F_* \times \psi_{EFF}(i-x_*,j-y_*)}$

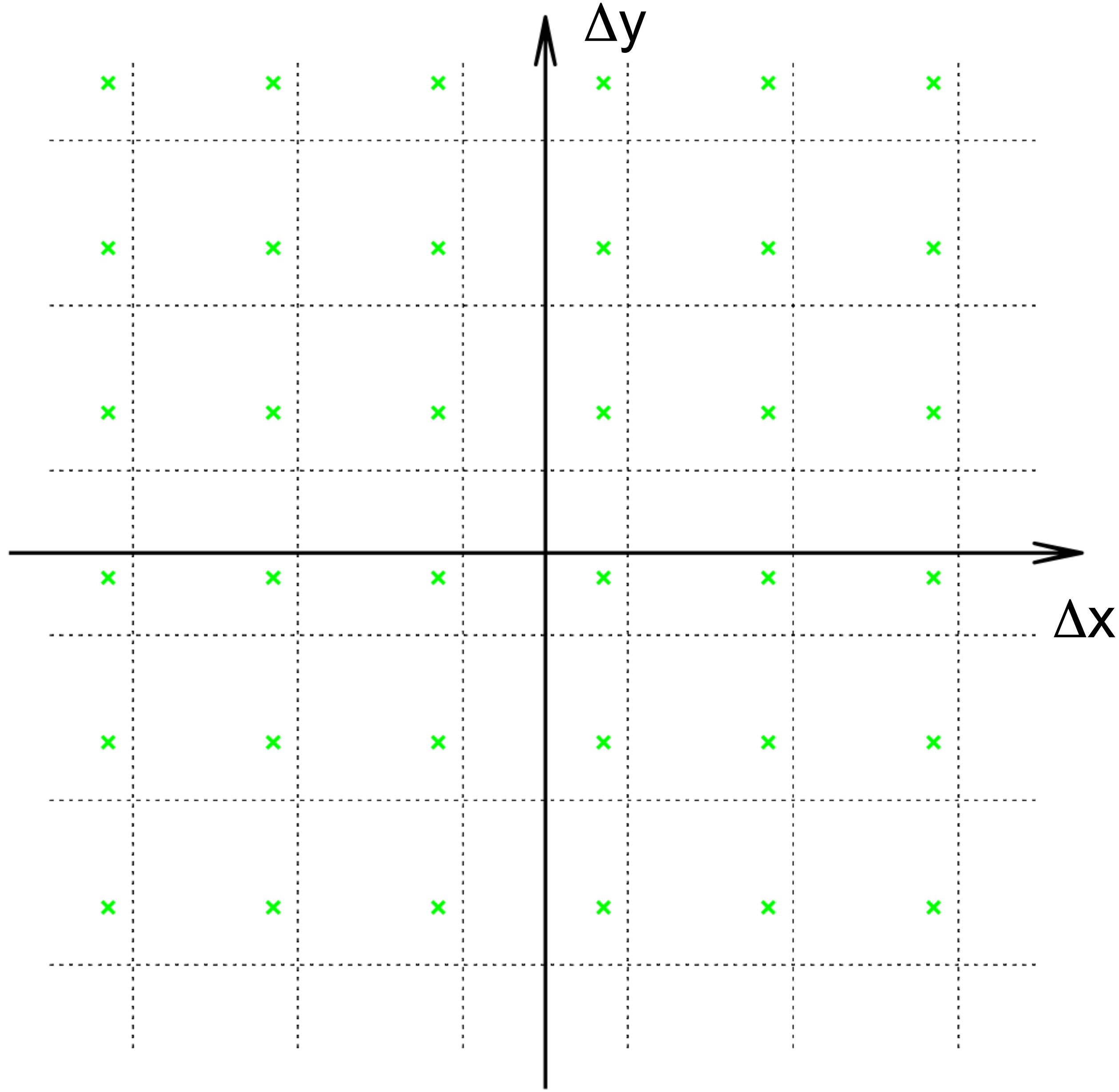
- **How to "see" it:**

$$\boxed{\psi_{EFF}(\Delta x,\Delta y) = (P_{ij} - S)/F_*}$$

  - Where: $\Delta x = i - x_*$, etc
  - We have to know (x_*,y_*) and F_*



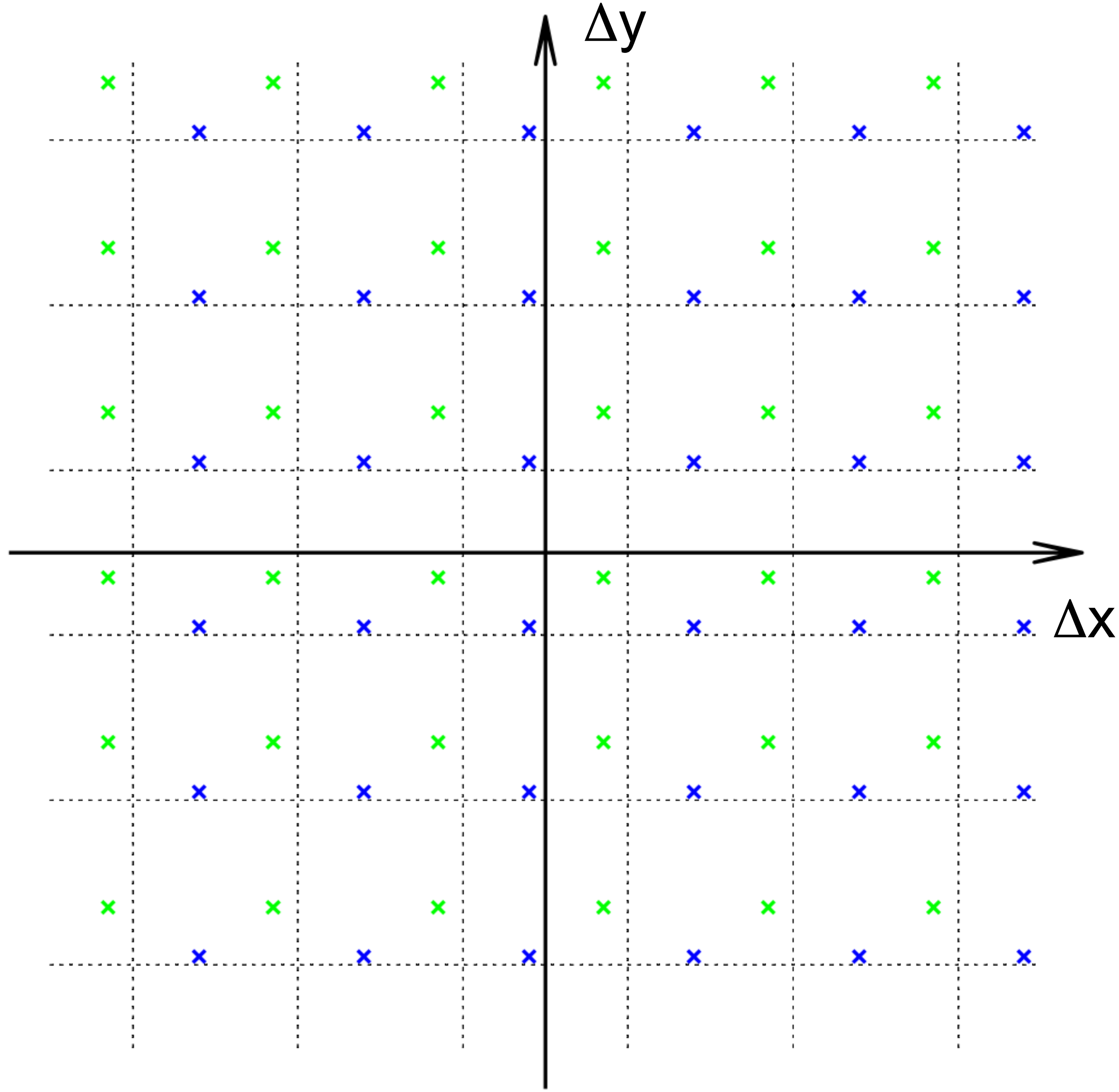
How a single star samples $\psi_E(\Delta x, \Delta y)$



- A single star has an array of pixels about its center.
- Each pixel contains a fraction of its flux.
- Each pixel reports ψ_E at one point in ψ_E's domain.

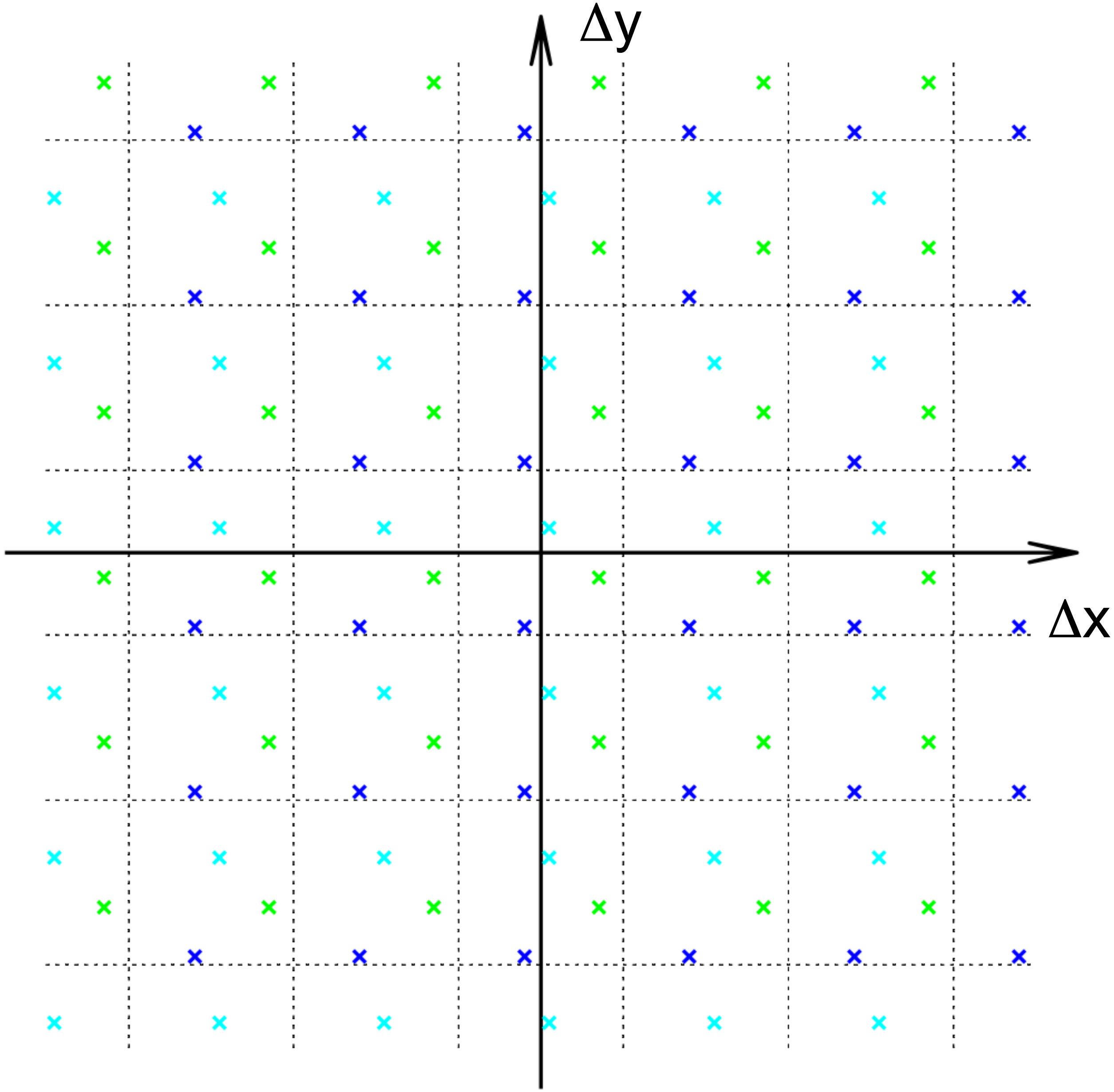
How two stars sample $\psi_E\,(\Delta x, \Delta y)$

- In general, the two stars will be at different pixel phases.
- This gives us a different array of samples of ψ_E



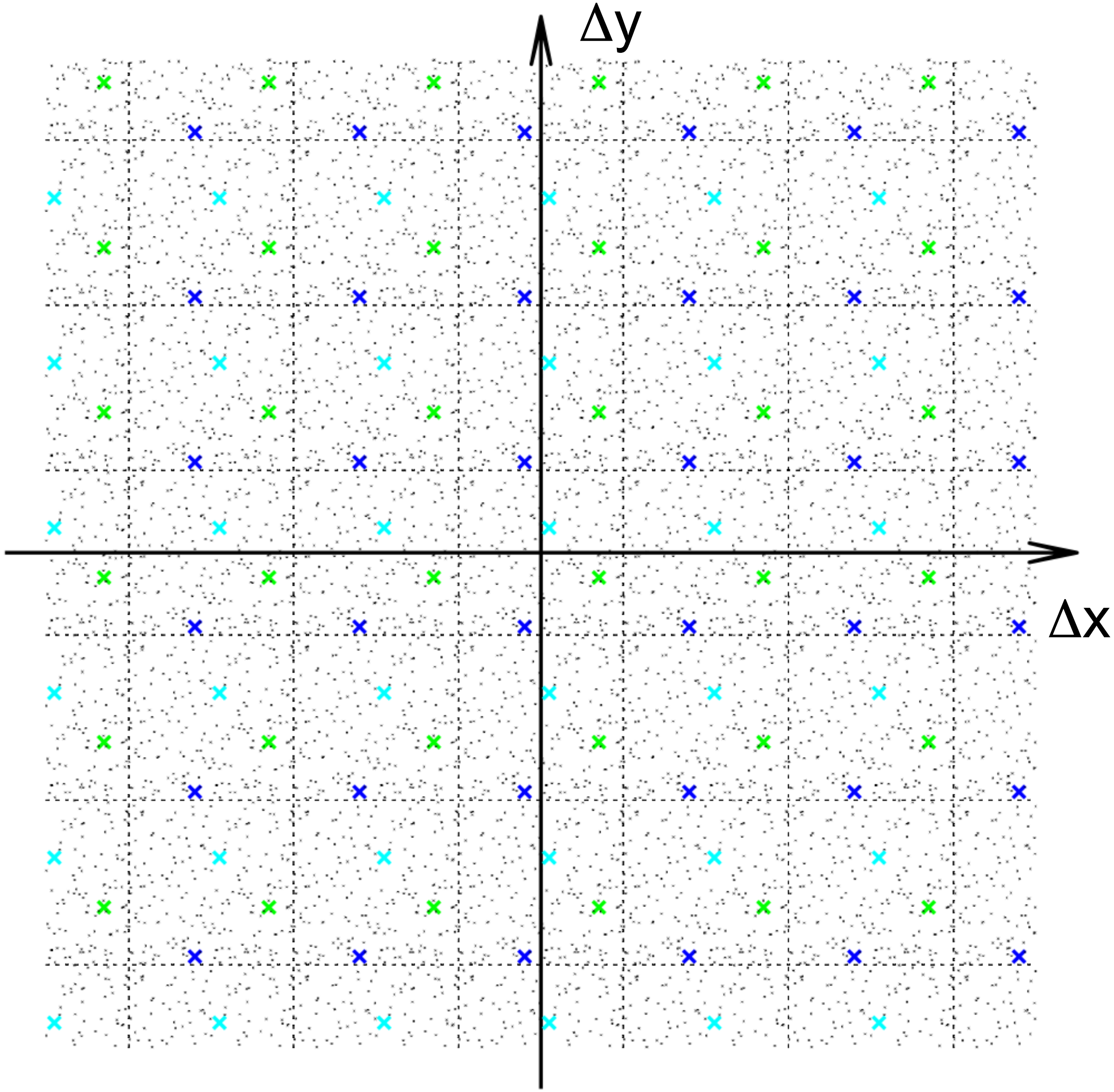
How three stars sample $\psi_E (\Delta x, \Delta y)$

- A third star will give yet more variety in our sampling of ψ_E



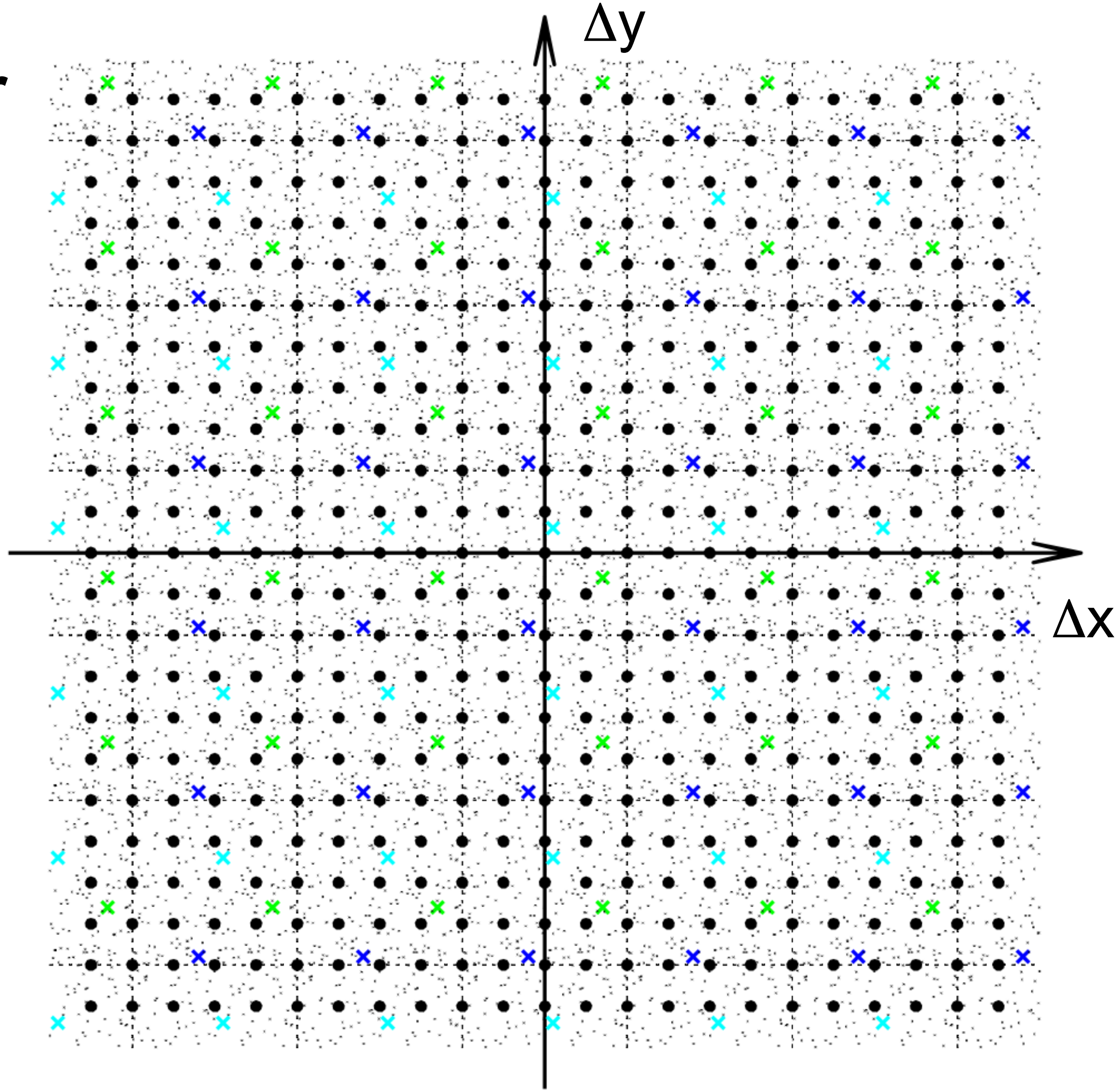
How 200 stars sample ψ_E (Δs, Δy)

- A large number of stars gives us an almost even coverage of ψ_E across its 2-D domain.

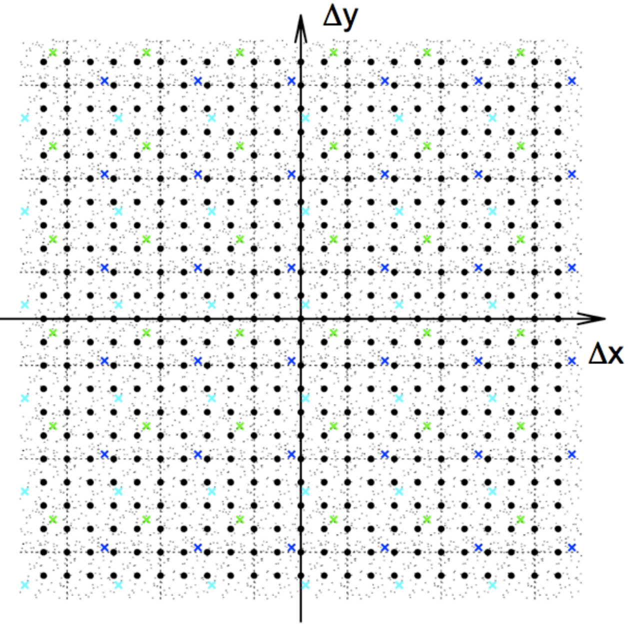


How to solve for $\psi_E(\Delta x, \Delta y)$

- A regularly-spaced array of grid-points
- Specify value of ψ_E at those points to best-fit the data.



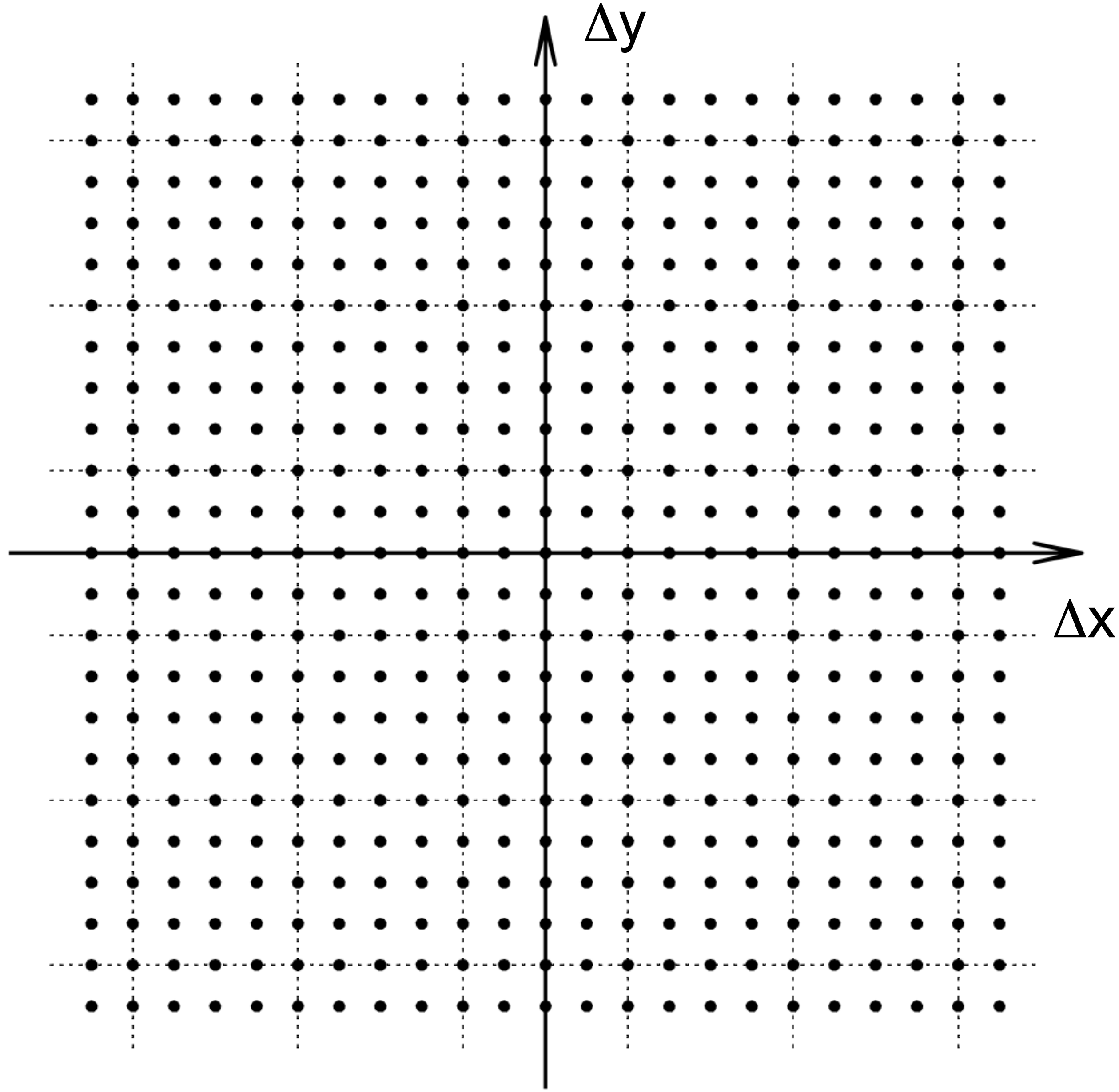
“Seeing” ψ_{EFF} Directly



Anderson & King 2000 PASP

The model of $\psi_E(\Delta x, \Delta y)$

- Tabulated values of ψ_E at this array of points across its domain.



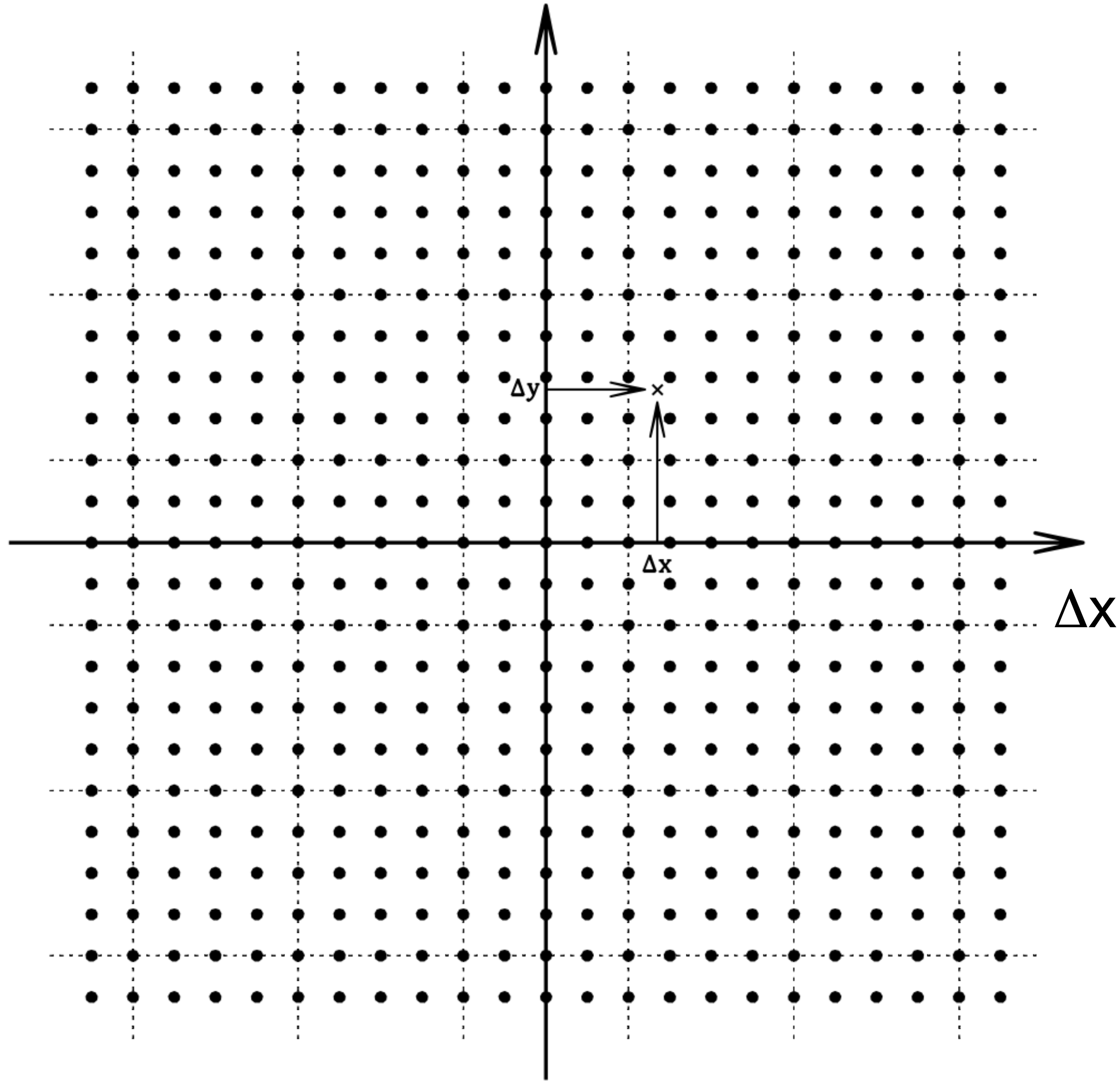
How to use $\psi_E(\Delta x, \Delta y)$

Need to know:

"What fraction of light should land in a pixel, if the pixel is centered at $(\Delta x, \Delta y)$ relative to the point source?"

Need to interpolate:

→ Use bi-cubic interpolation



1) How to find the PSF?

2) How to use the PSF?

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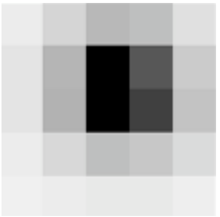
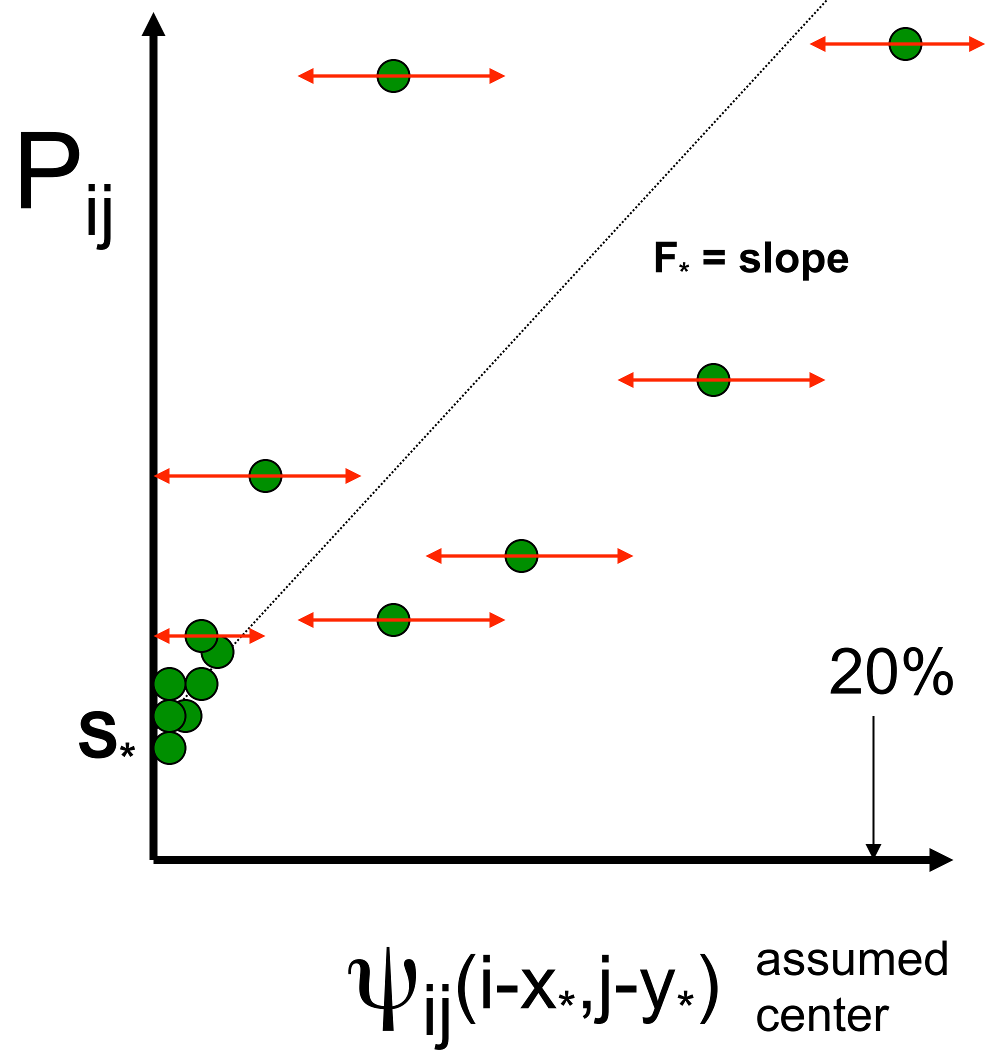


Fitting for Flux and position:

$$P_{ij} = S + F_* \times \psi_{ij}$$

- Nice, linear equation!
- Which pixels to use?



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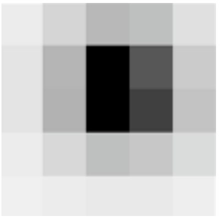

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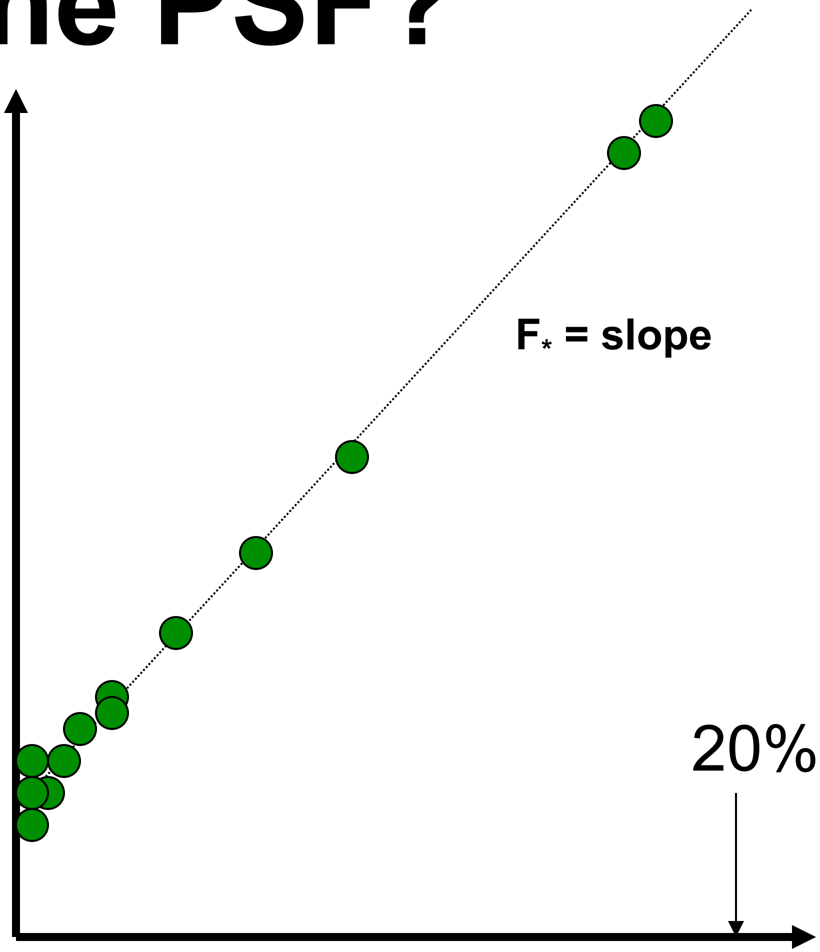
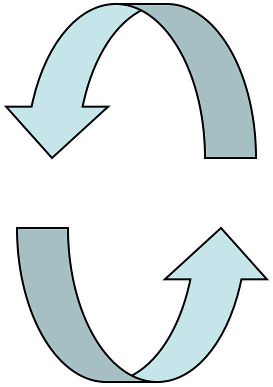


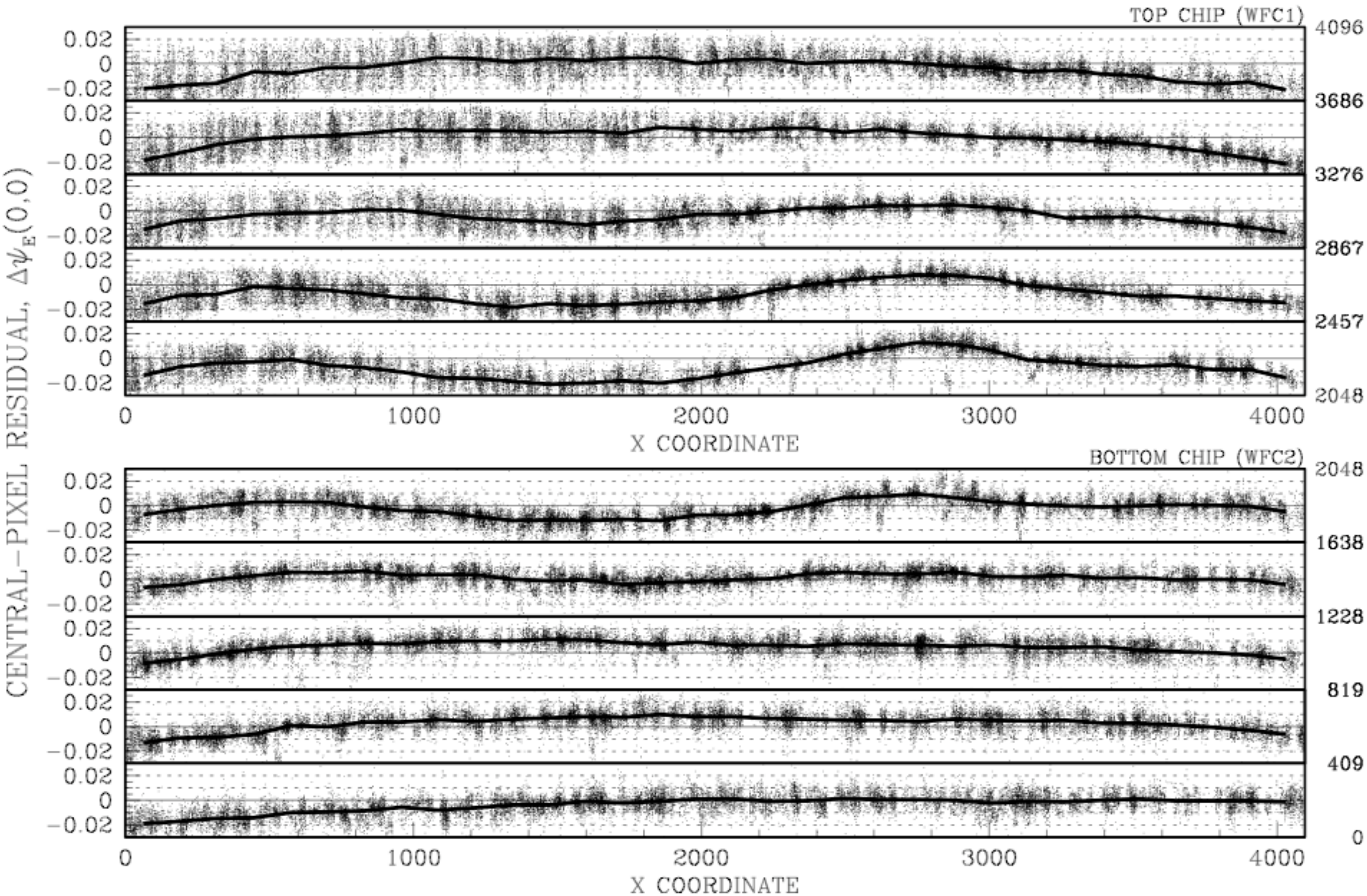
PSF: Finding -vs- Using

- **Degeneracy**:
  - Finding ψ_{EFF} requires (x,y,f)
  - Finding (x,y,f) requires ψ_{EFF}
- **Iteration**
  - Dithers break the degeneracy!



Higher-Level PSF Issues…

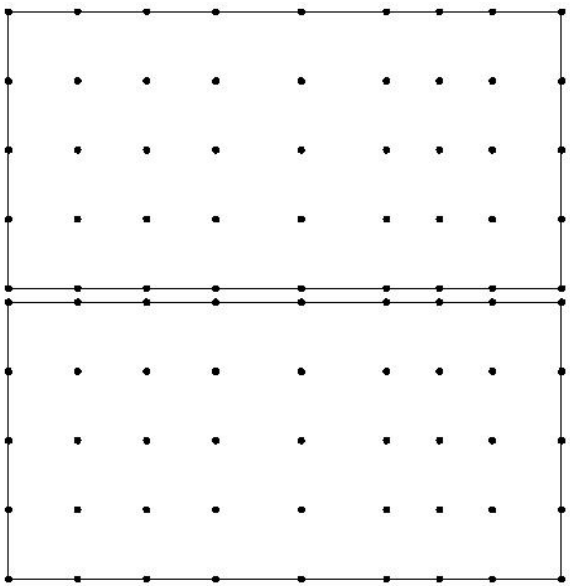
- **Spatial variability…**

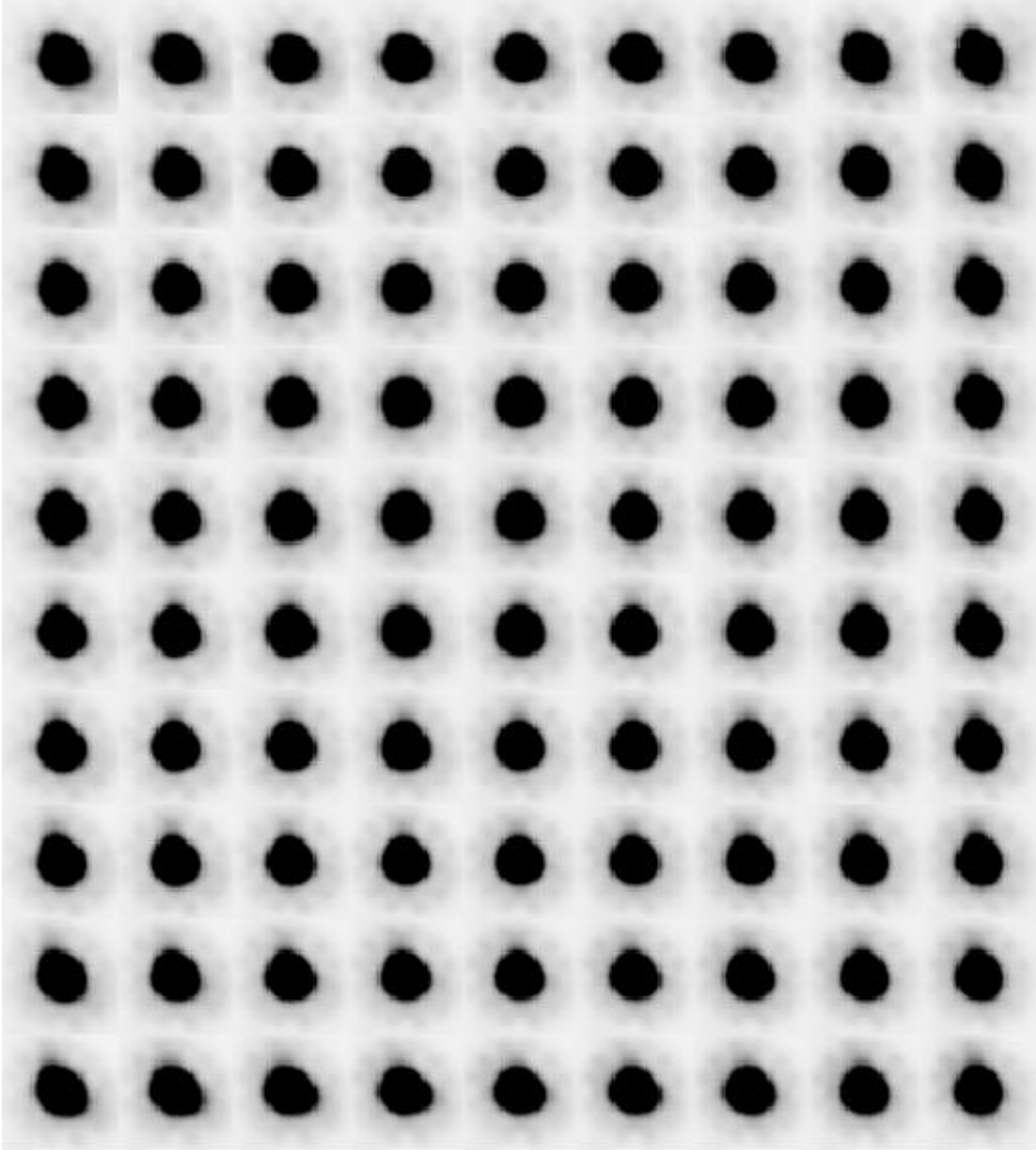


Higher-Level PSF Issues…

- **Spatial variability…**

Array of PSFs for F606W ACS

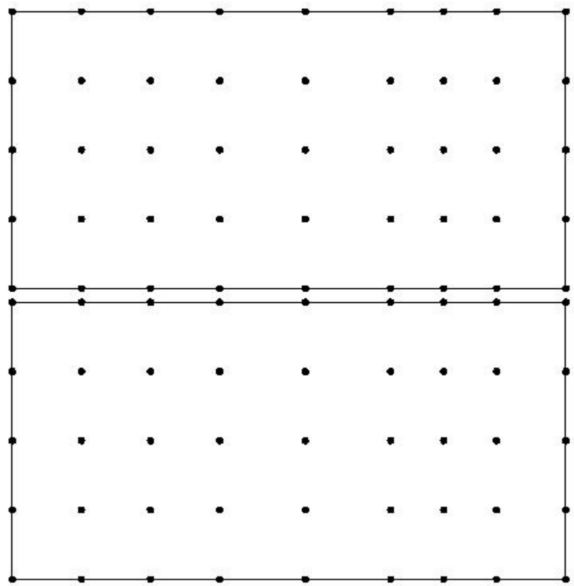


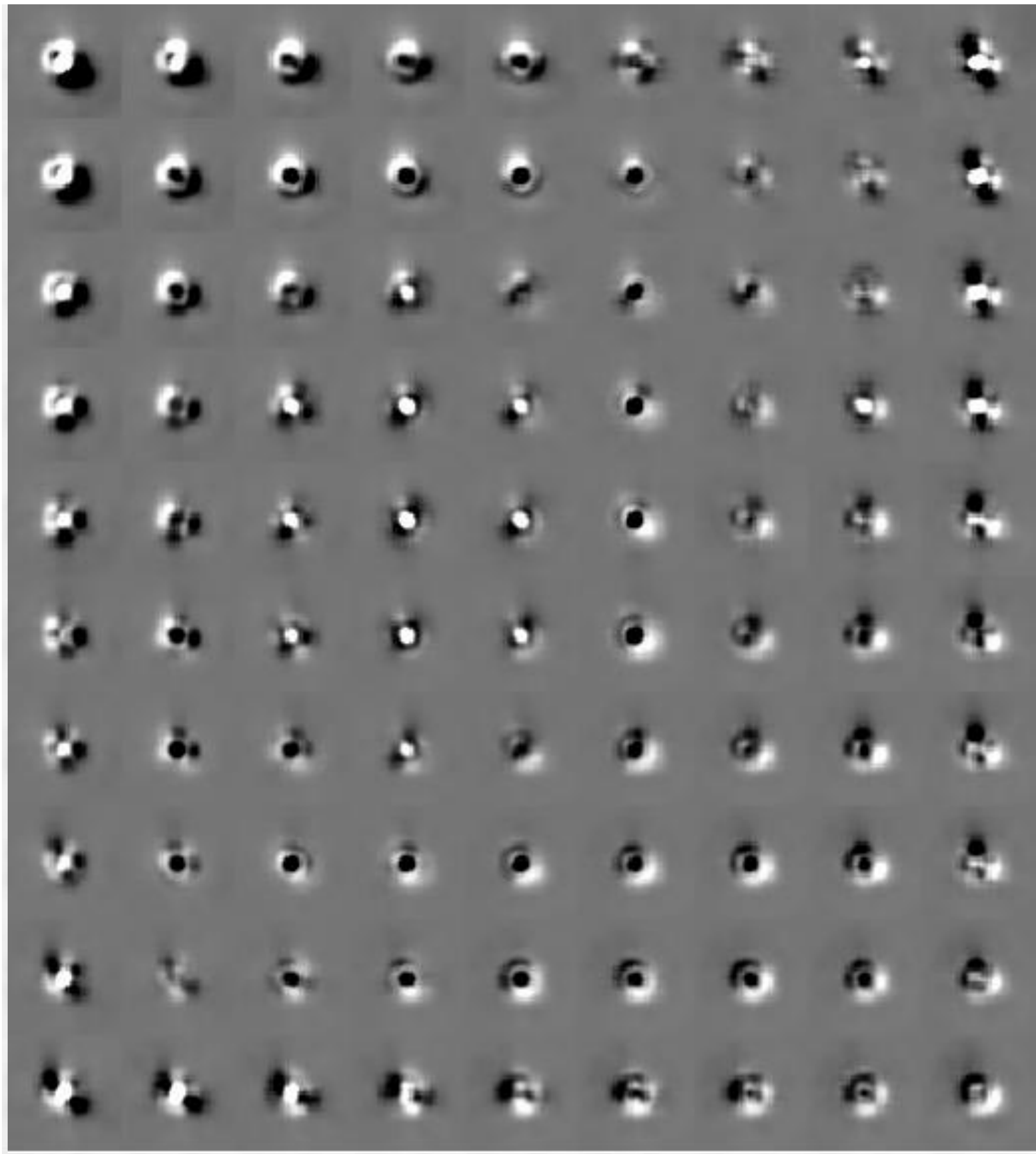


Higher-Level PSF Issues…

- **Spatial variability…**

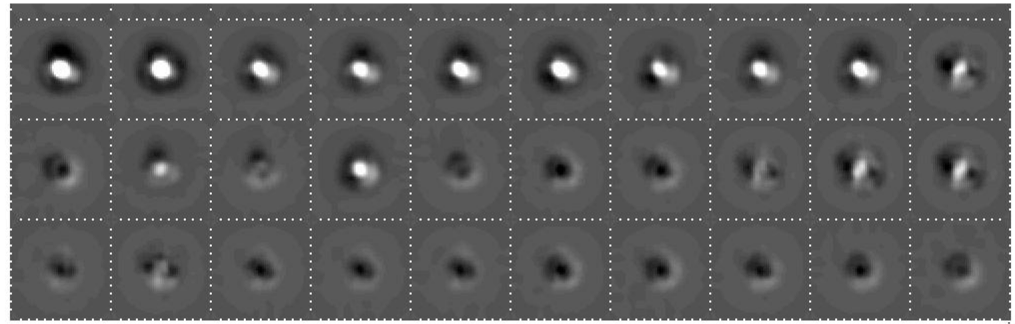
Core intensity varies by ±10% over scales of ~500 pixels.

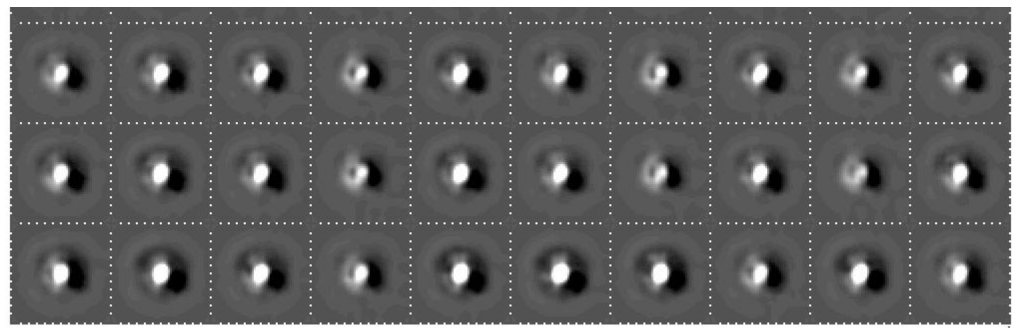




Higher-Level PSF Issues…

Pre-SM4

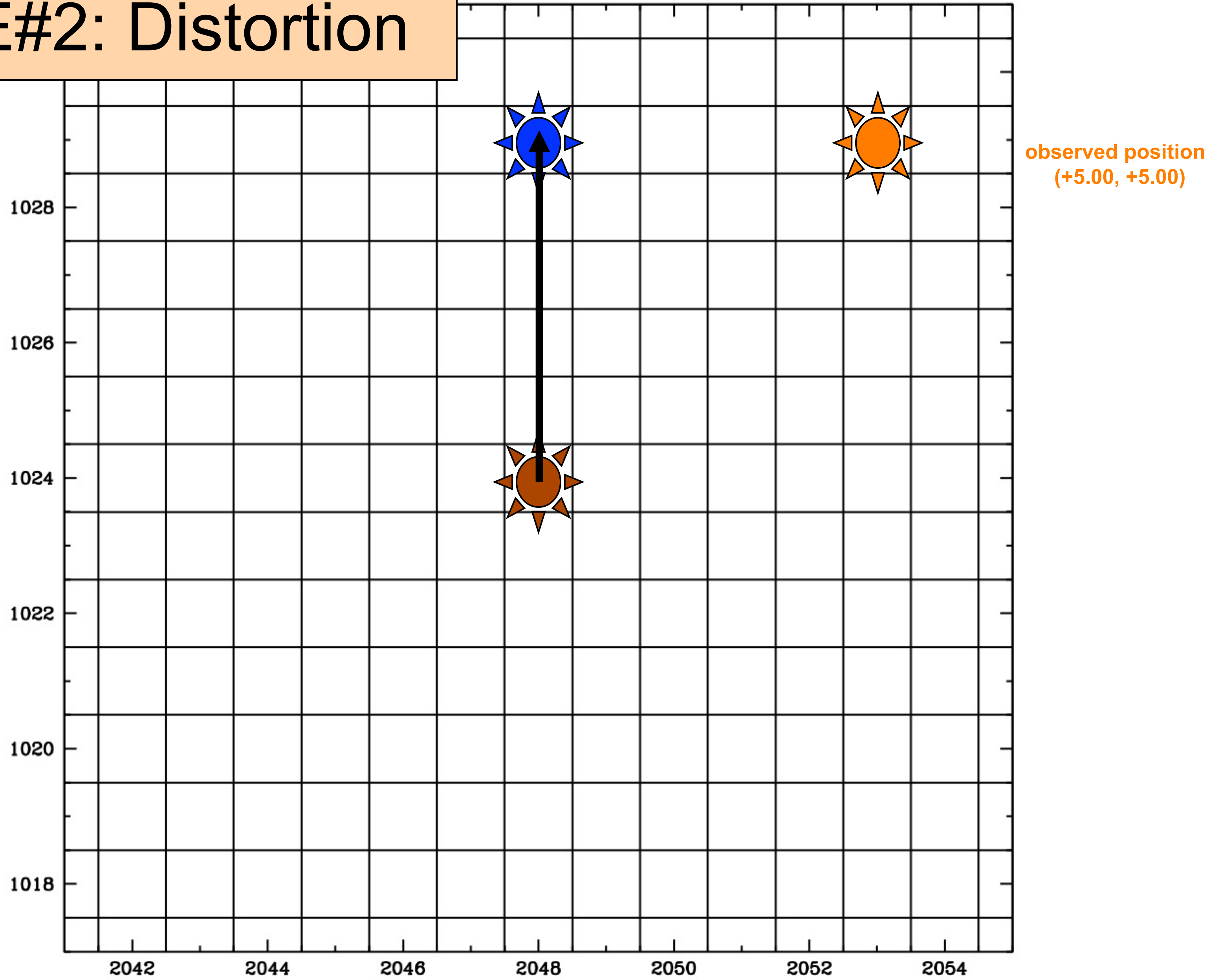


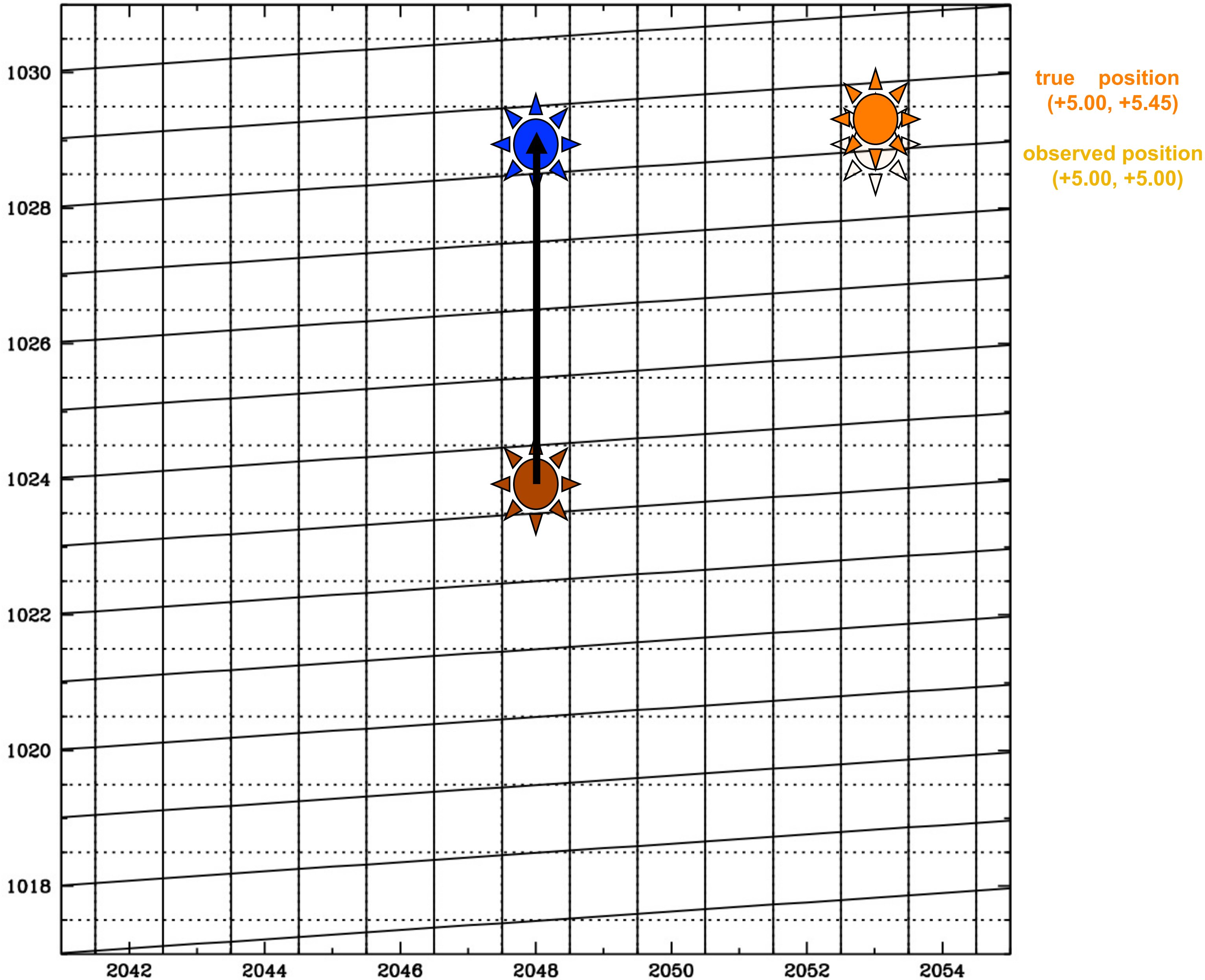


Post-SM4

- **Spatial variability**
- **Time variability**
  - Breathing: +/- 2%
  - Hybrid models:
    - $PSF(x,y;t)=PSF(x,y)+PSF(t)$
    - Good for ACS, ok for UVIS
  - Long-term variability (ACS)
- **How to define "center" ?**
  - Peak? Centroid? Point of Symmetry?
  - Cross-talk with distortion
- **Pixel-response function: $\Pi(\Delta x,\Delta y)$**
  - Included naturally
- **Color variability:** ~0.002 pixel (extreme: 0.02 pixel)

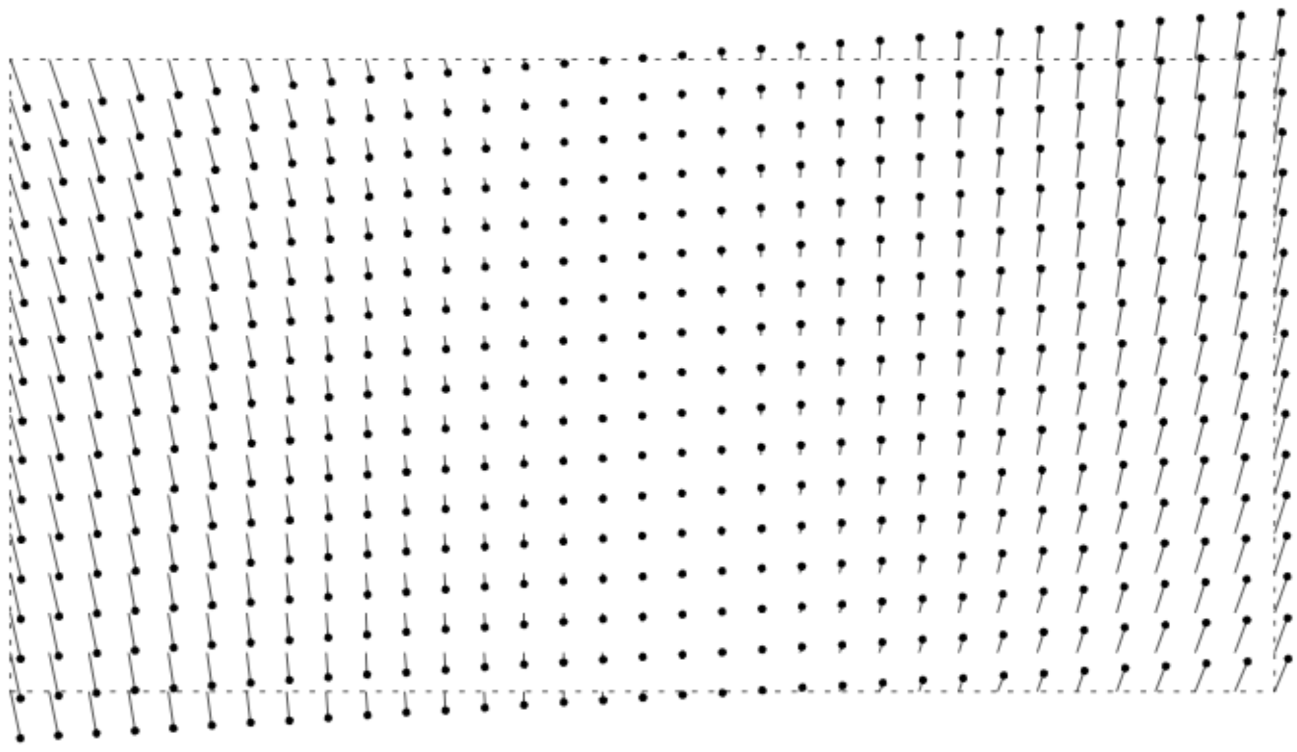
ISSUE#2: Distortion





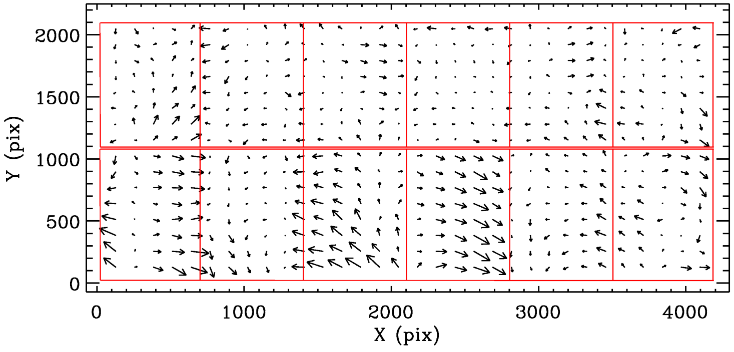
1030
1028
1026
1024
1022
1020
1018
2042
2044
2046
2048
2050
2052
2054
true position
(+5.00, +5.45)
observed position
(+5.00, +5.00)

Distortion

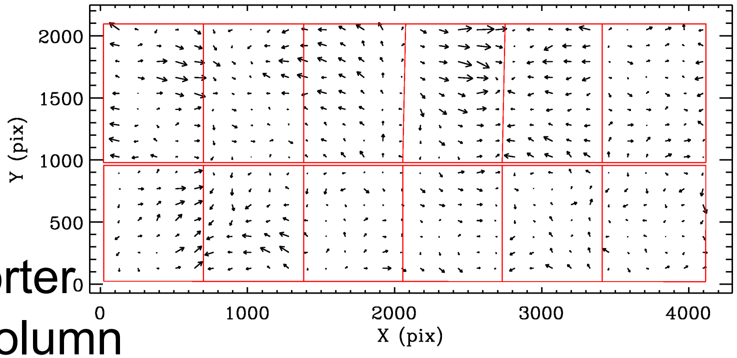


WFC/ACS DISTORTION

Sources of Distortion



1) **Geometric optics:**
   - Linear "skew": 500 pixels over 2000
     → Parallelogram pixels
   - Non-linear: 50 pixels over 2000
2) **Filters introduce distortion**
   - Offsets, scale changes
   - "Fingerprint" of ~0.05 pixel
3) **Detector "stitching" defects**
   - WFPC2: every 34.1333th row 3% shorter
   - ACS/WFC: pattern every 68.2666th column
   - WFC3/UVIS: 2-D zones
4) **CTE losses...**
   - ACS Solution now available (UVIS coming soon)



UVIS

Need empirical approach…
Plot everything against
everything else…

ISSUE#1: Undersampling/PSFs
ISSUE#2: Distortion
ISSUE#3…

Transformations

All HST astrometry is differential astrometry

- → Guide-star precision ~ 0.5″ (improved from 1.5″!)
- → No reference stars in typical field
- → We never know the true pointing

Always need to define a *local* reference frame

- → Pixels/positions have only relative meaning.
- → Choosing a frame/population you know something about
    - → absolute $\mu = 0$ (galaxies)
    - → average μ = same (clusters)
    - → average μ = unchanging (field)
- → Allow for breathing effects
    - → 6-param transformations, or go local

ISSUE#1: Undersampling/PSFs
ISSUE#2: Distortion
ISSUE#3: Transformations

Good News: All manageable issues

Undersampling/PSFs:

- → Ways to model accurately, get 0.01-pixel positions
- → Libraries available, usually sufficient

Distortion:

- → Stable, model available, small variations, ~ 0.01 pixel

Transformations:

- → Can optimize for program

0.01 pixel error per exposure, **can be made random**

Bad news:

No one-size-fits-all solutions…

Astrometric Science with HST…

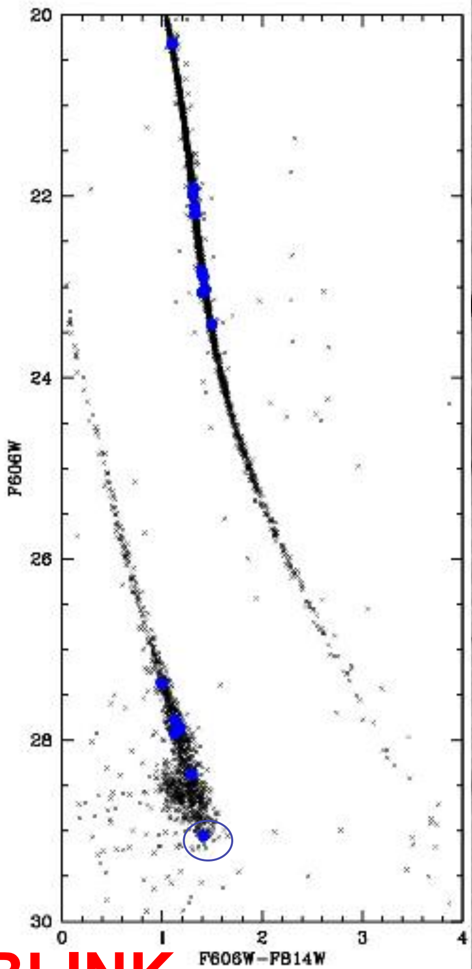
1) **Cluster Membership**
2) Absolute motions
3) Internal motions in clusters
4) **Microlensing applications**

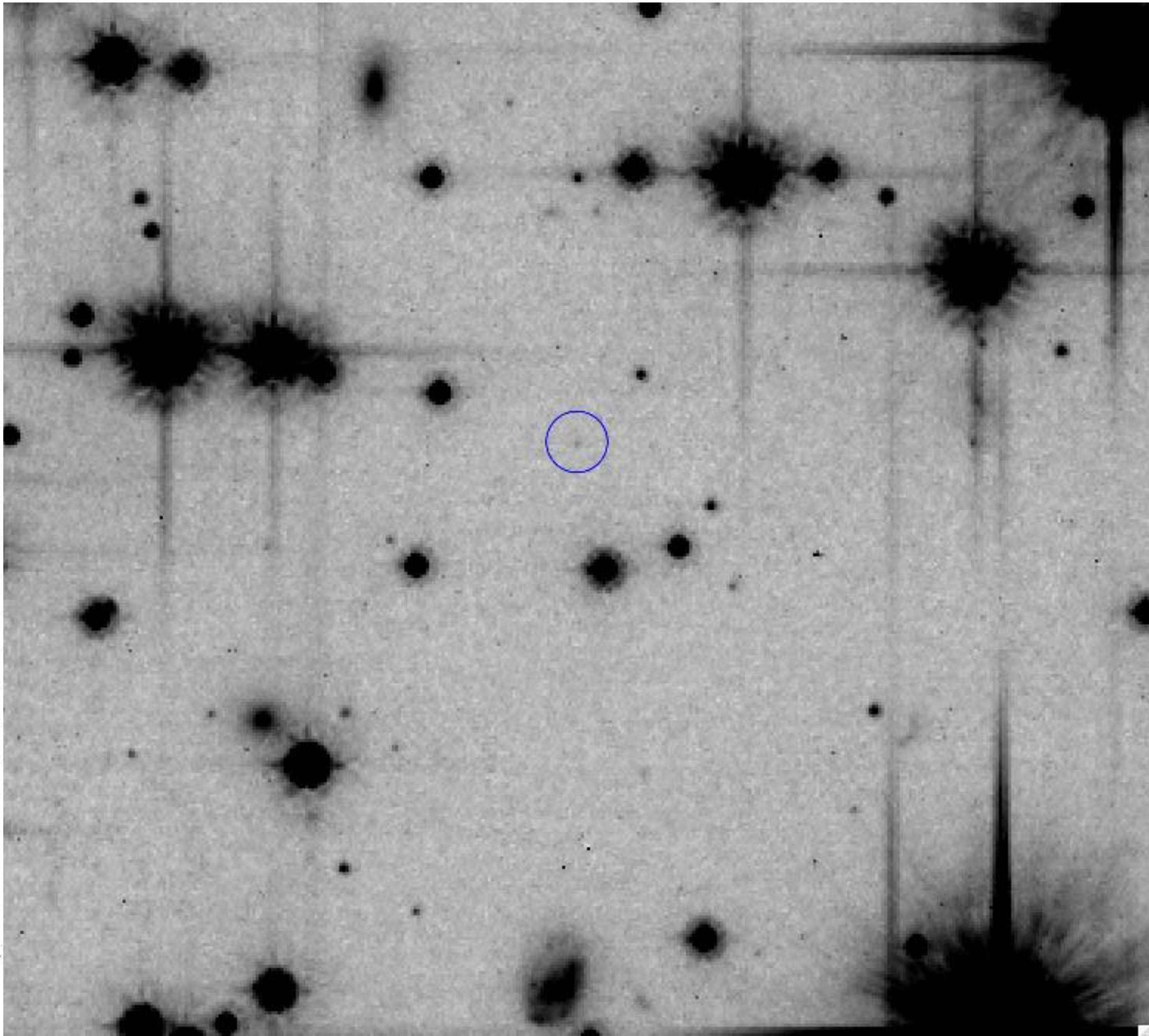
1) Bulk motions:

NGC6397

PI-Rich, UCLA

Proper-Motion Cleaning

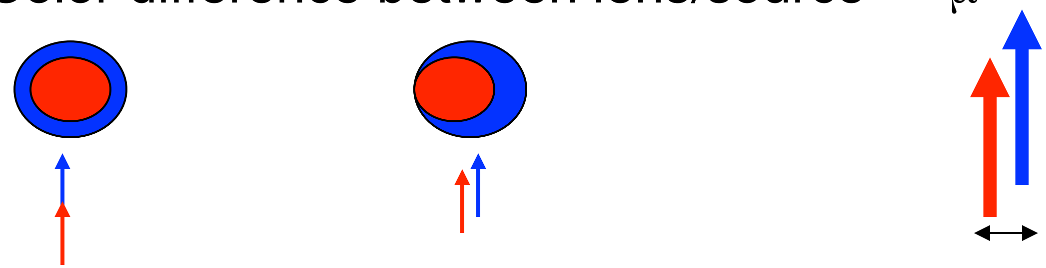




BLINK

4) Microlensing Applications (breaking degeneracies)

1) **Color-dependent centroid shift (1st moment)**
   - Color difference between lens/source → μ



During event **After event**

$f \times \mu = 0.6$ mas/2yr

Bennett et al 2006
OGLE-2003/BLG-235
MOA-2003/BLG-53

2) **De-blending (measure 2nd moment)**

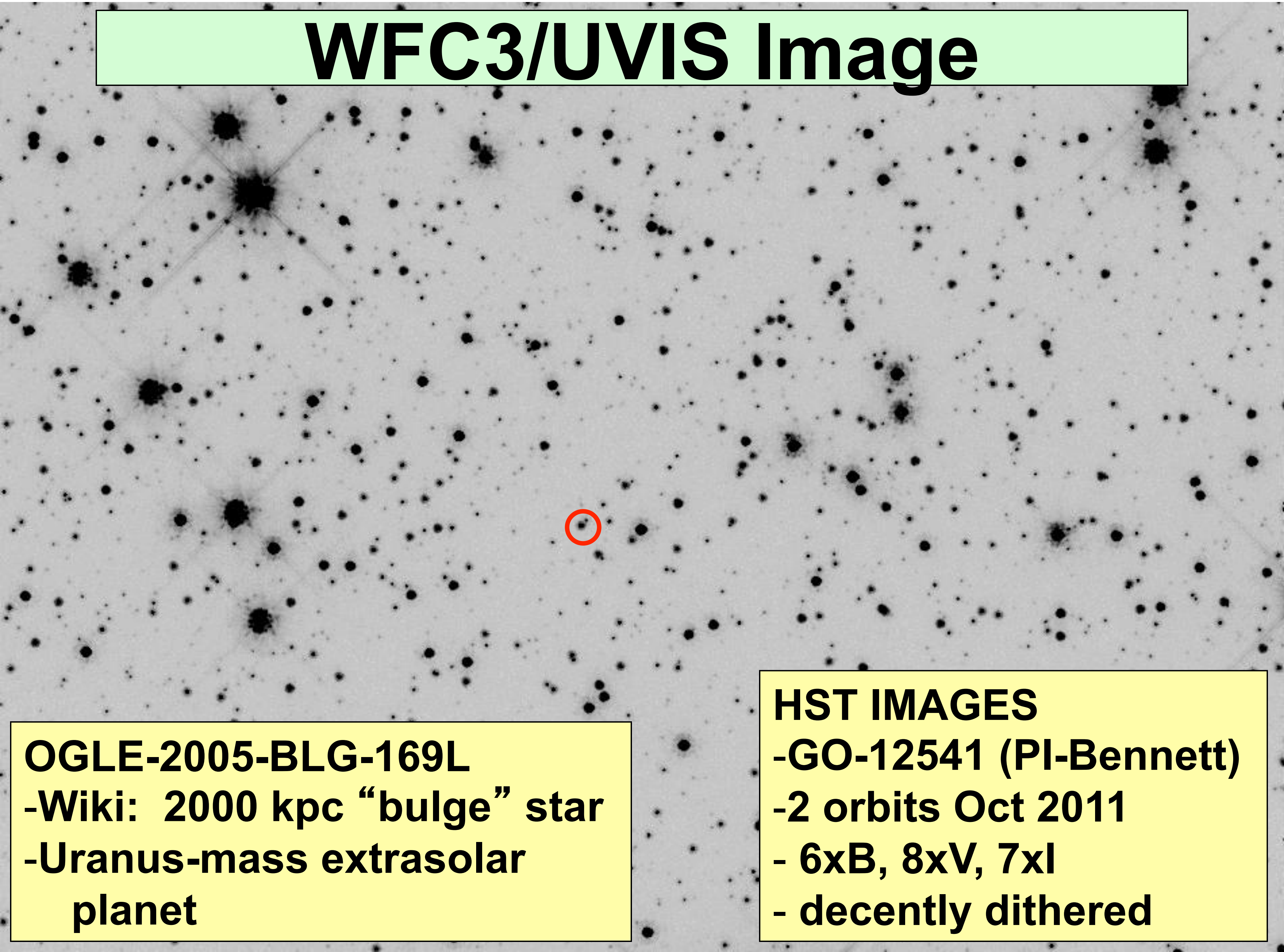
3) **Astrometry during the event**

2) De-blending:

OGLE-2005-BLG-169

Epoch 1 HST Observations

WFC3/UVIS Image

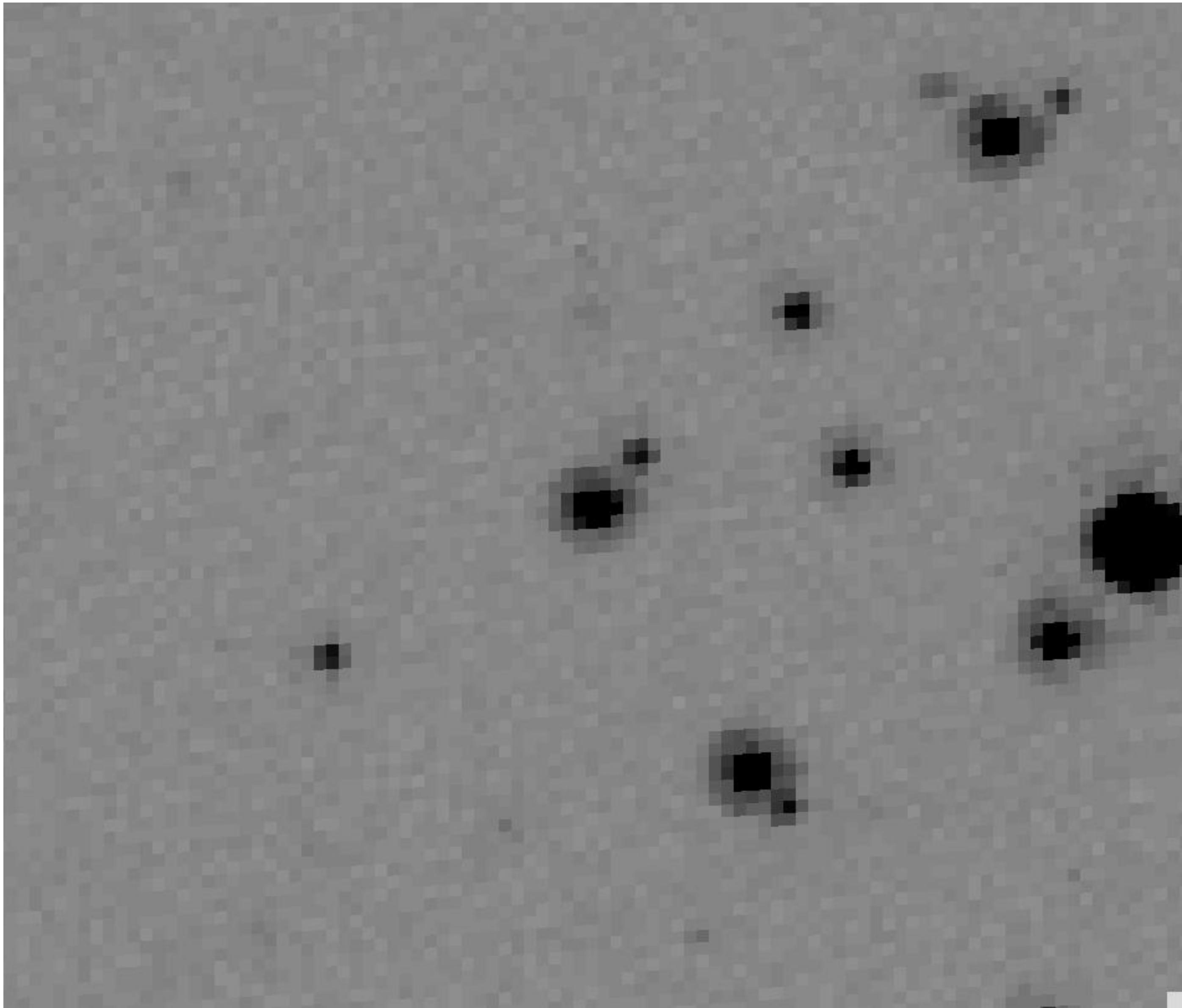


OGLE-2005-BLG-169L
-Wiki: 2000 kpc “bulge” star
-Uranus-mass extrasolar
 planet

HST IMAGES
-GO-12541 (PI-Bennett)
-2 orbits Oct 2011
- 6xB, 8xV, 7xI
- decently dithered

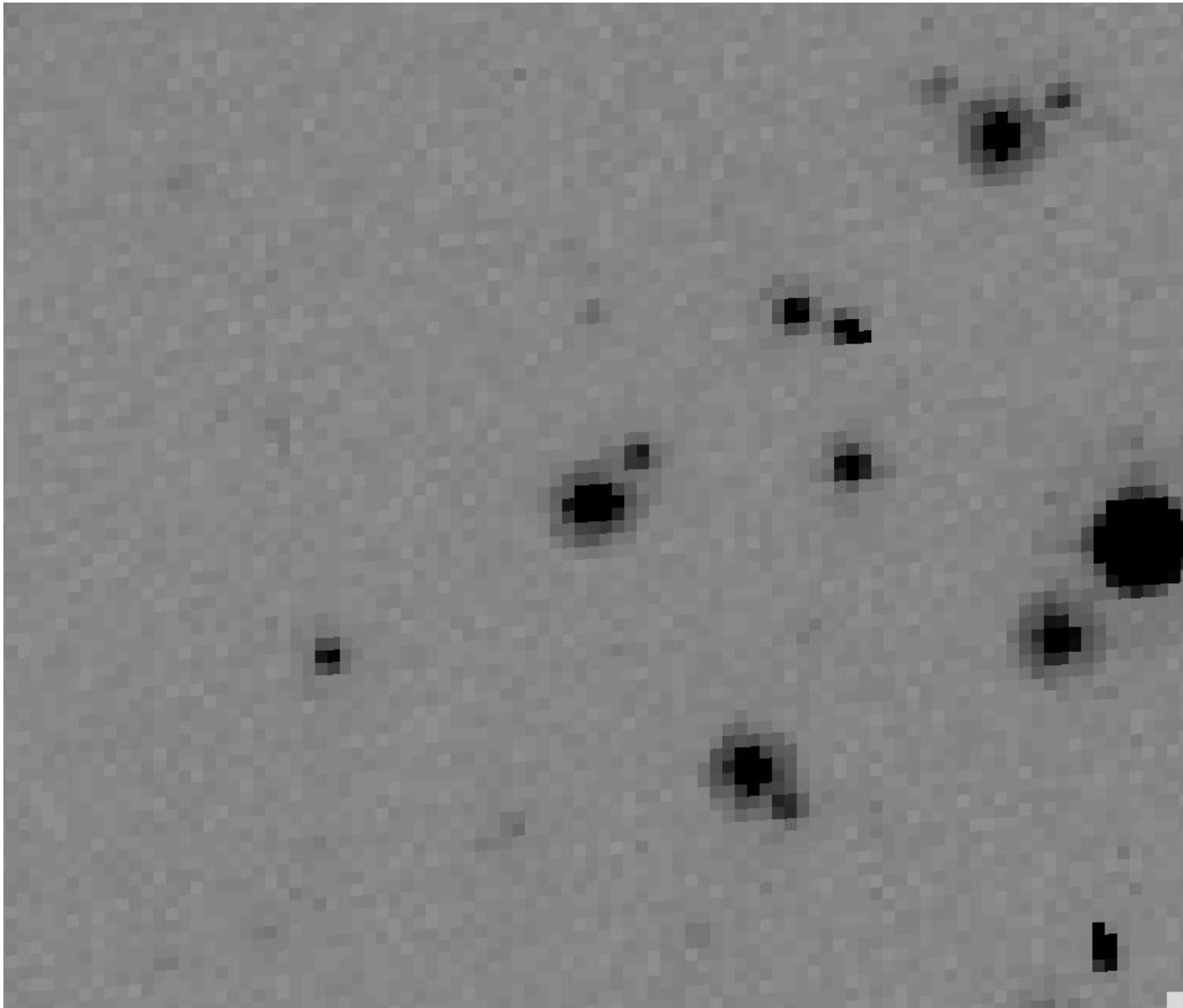
Seven F814W Observations

i_1



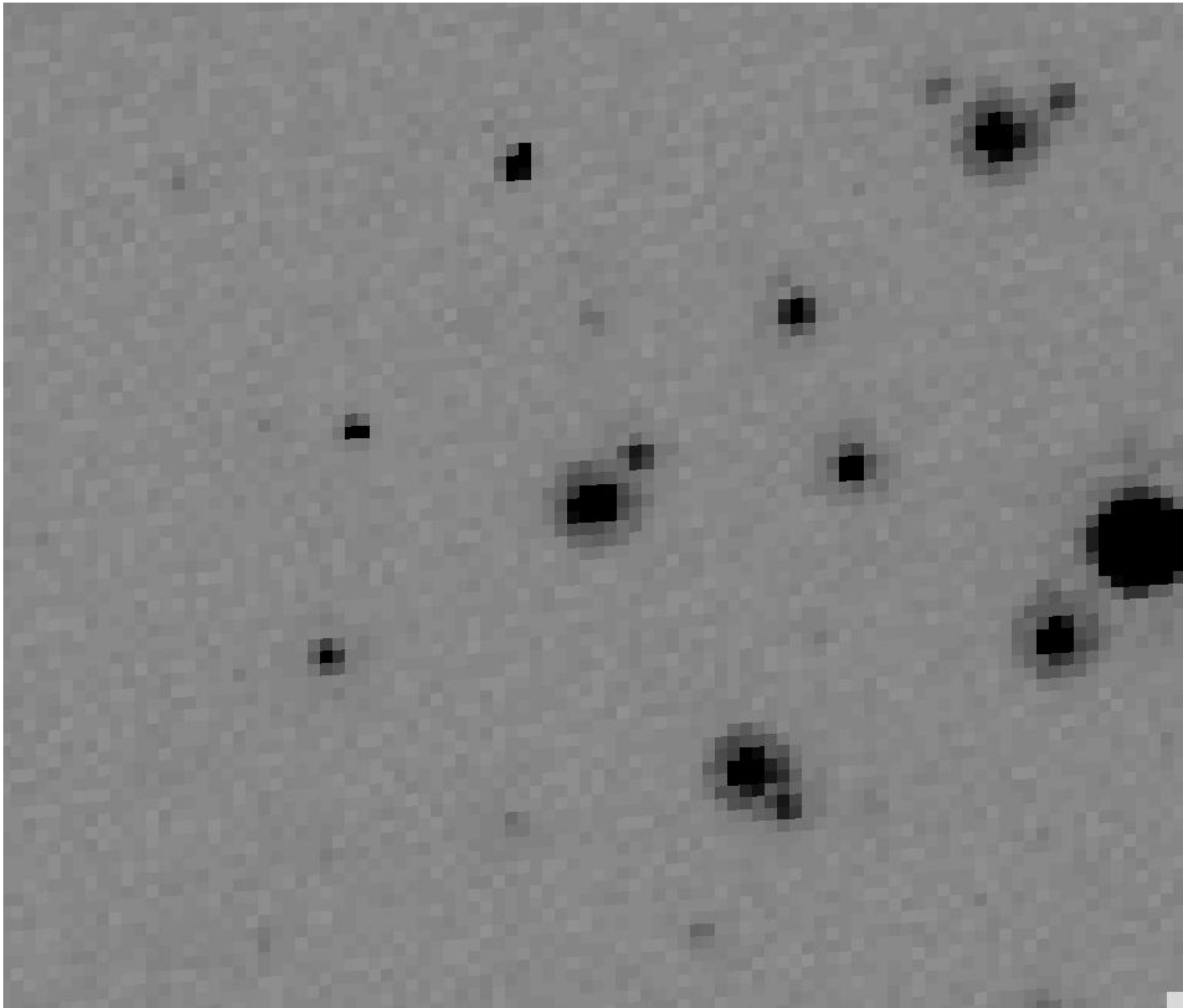
Seven F814W Observations

i_2



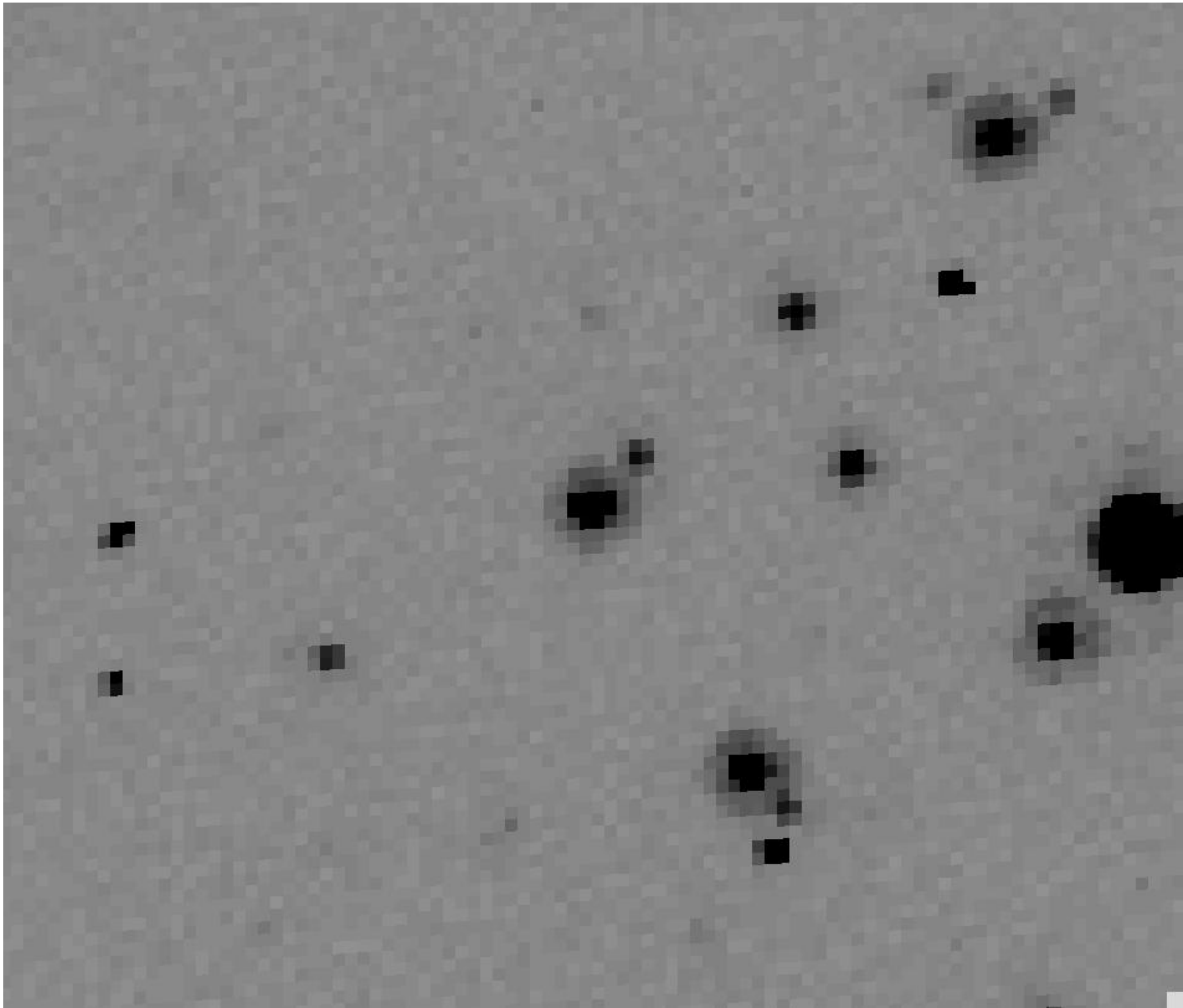
Seven F814W Observations

i_3



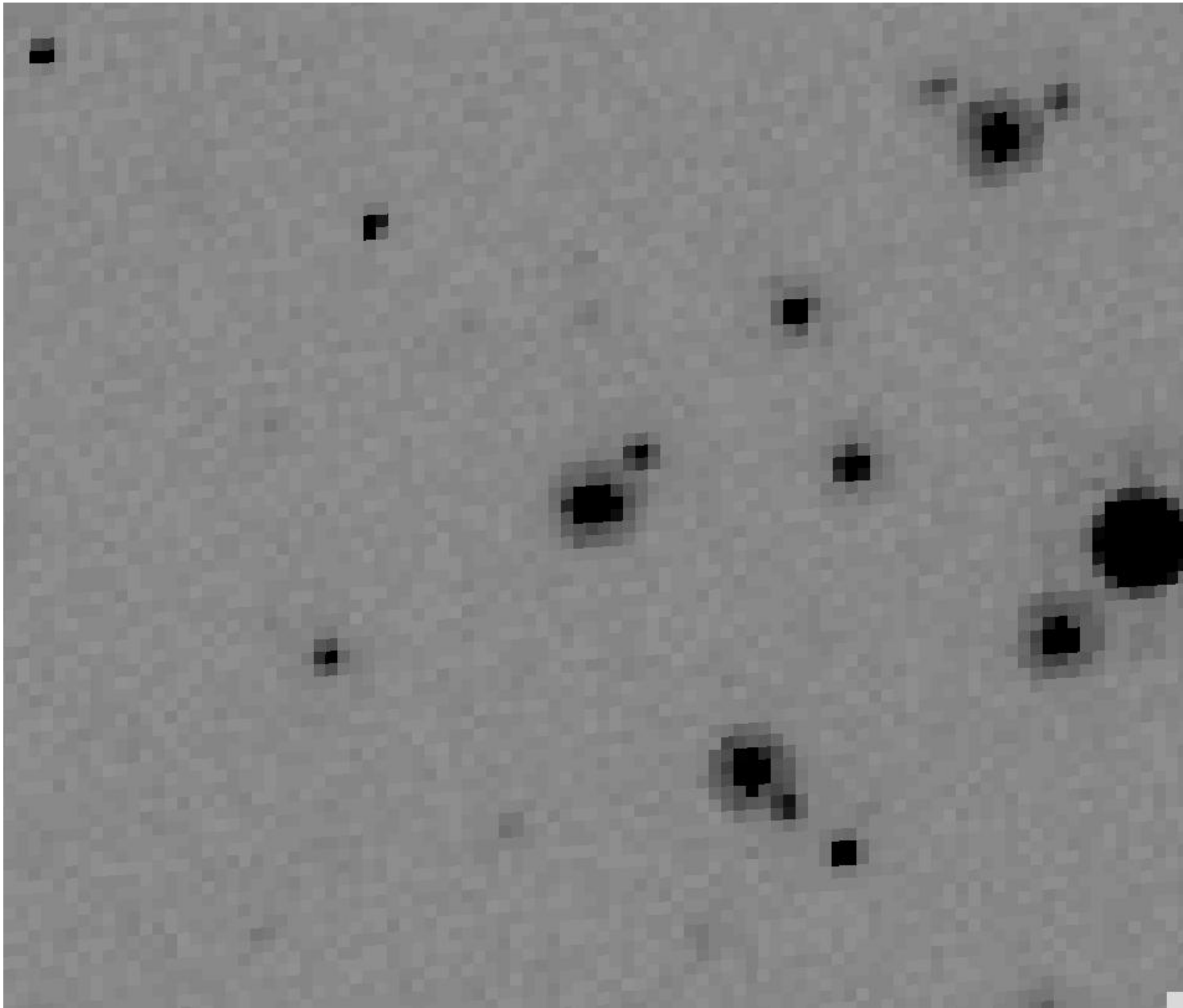
Seven F814W Observations

i_4



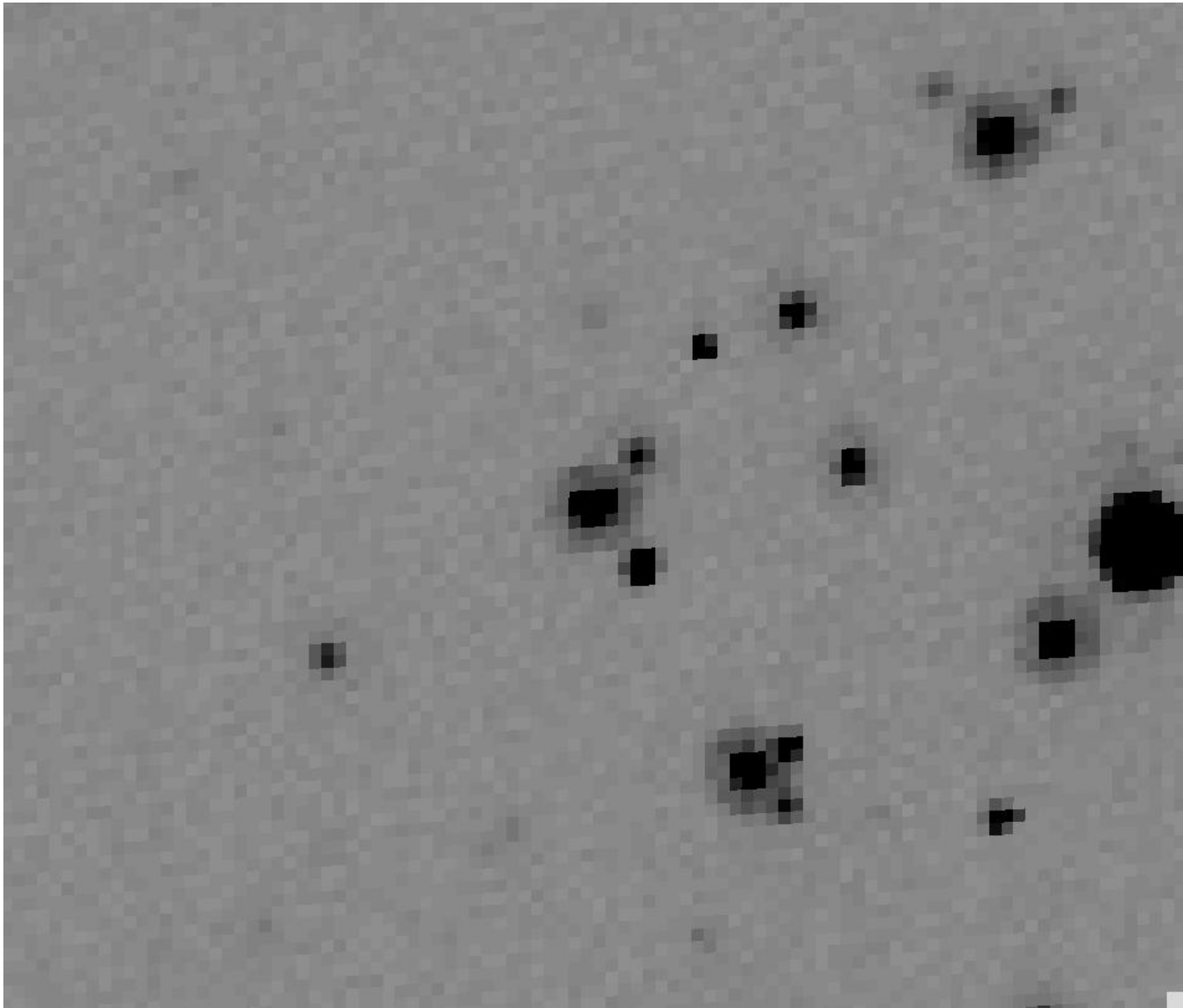
Seven F814W Observations

i_5



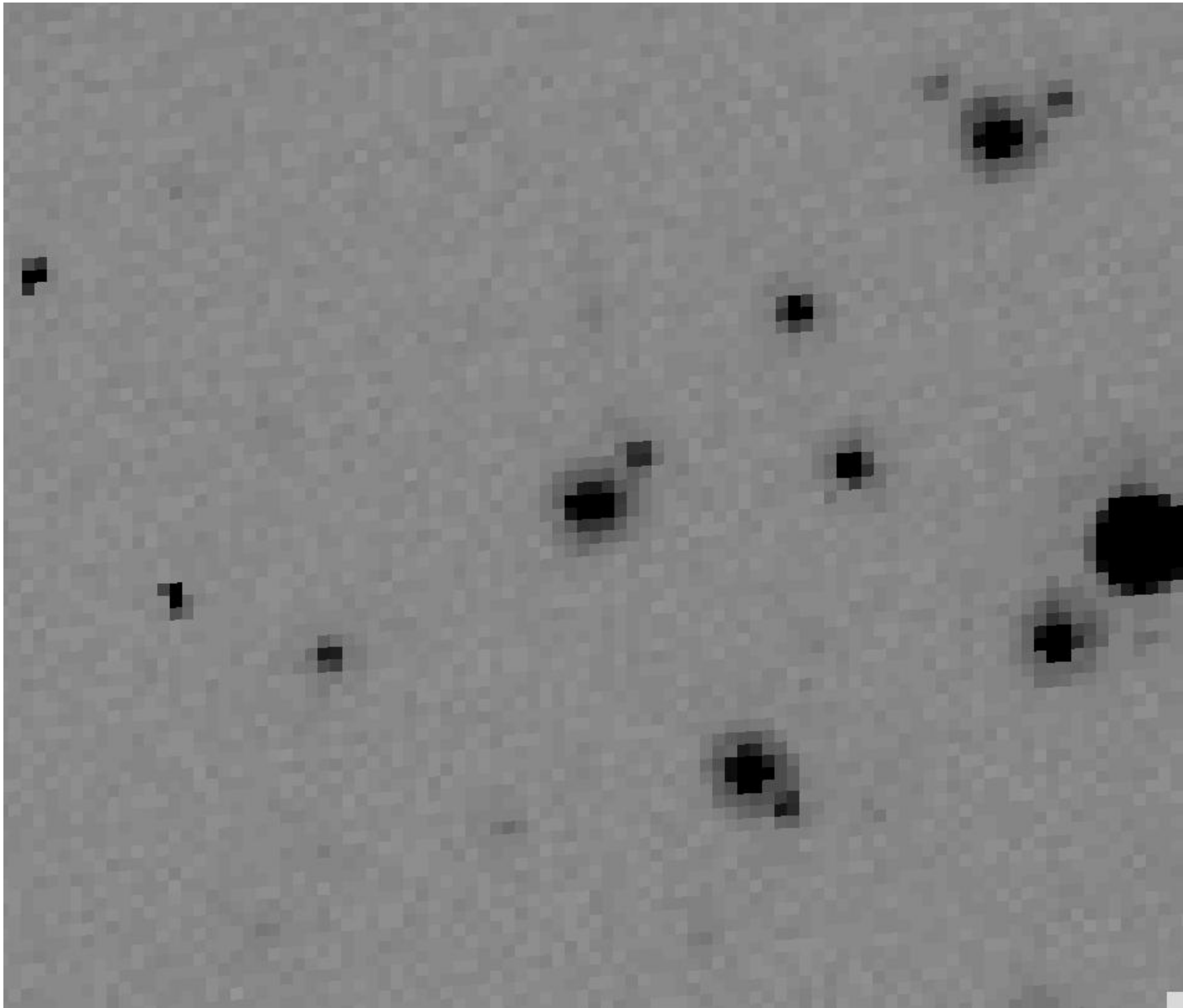
Seven F814W Observations

i_6

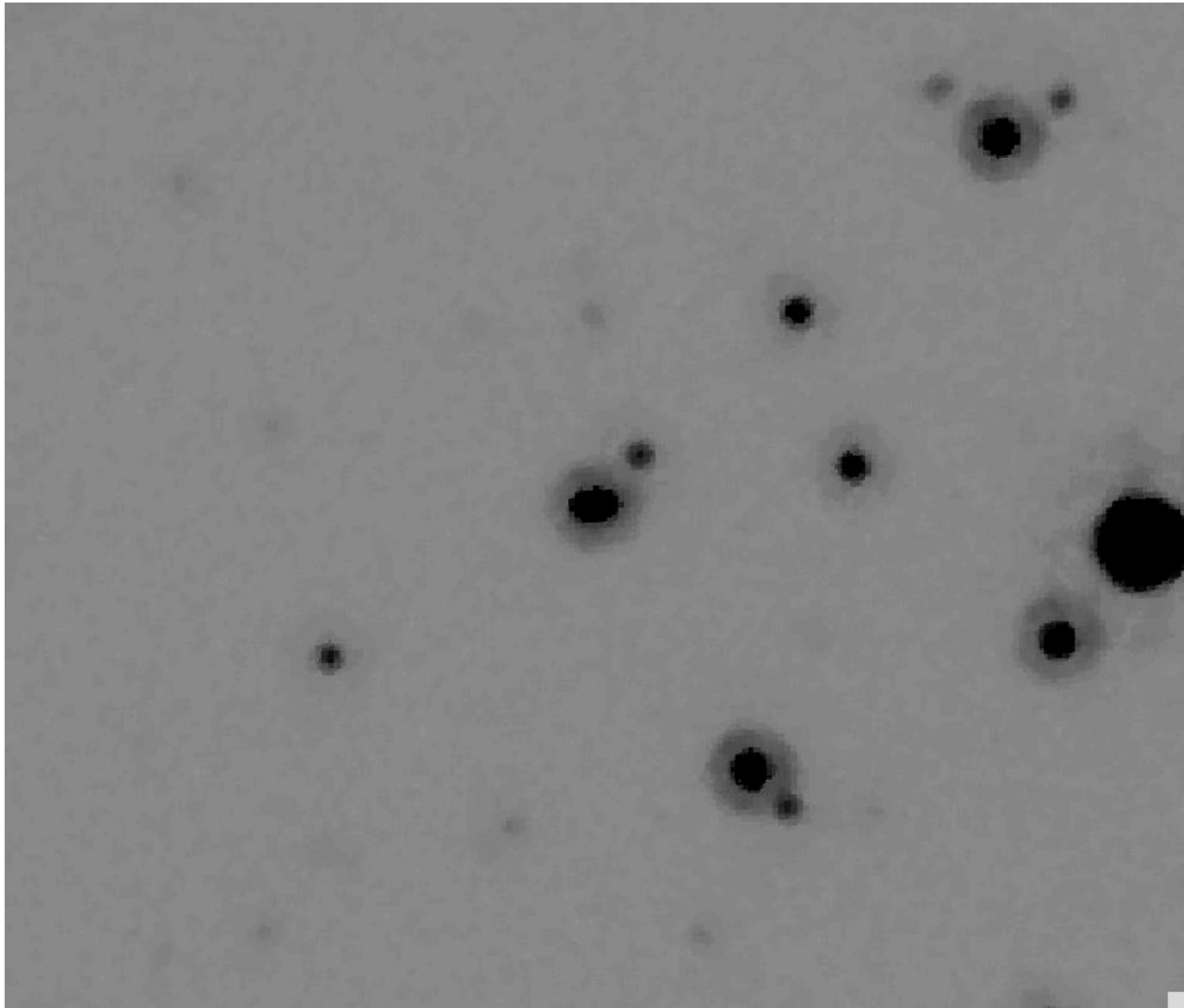


Seven F814W Observations

i_7

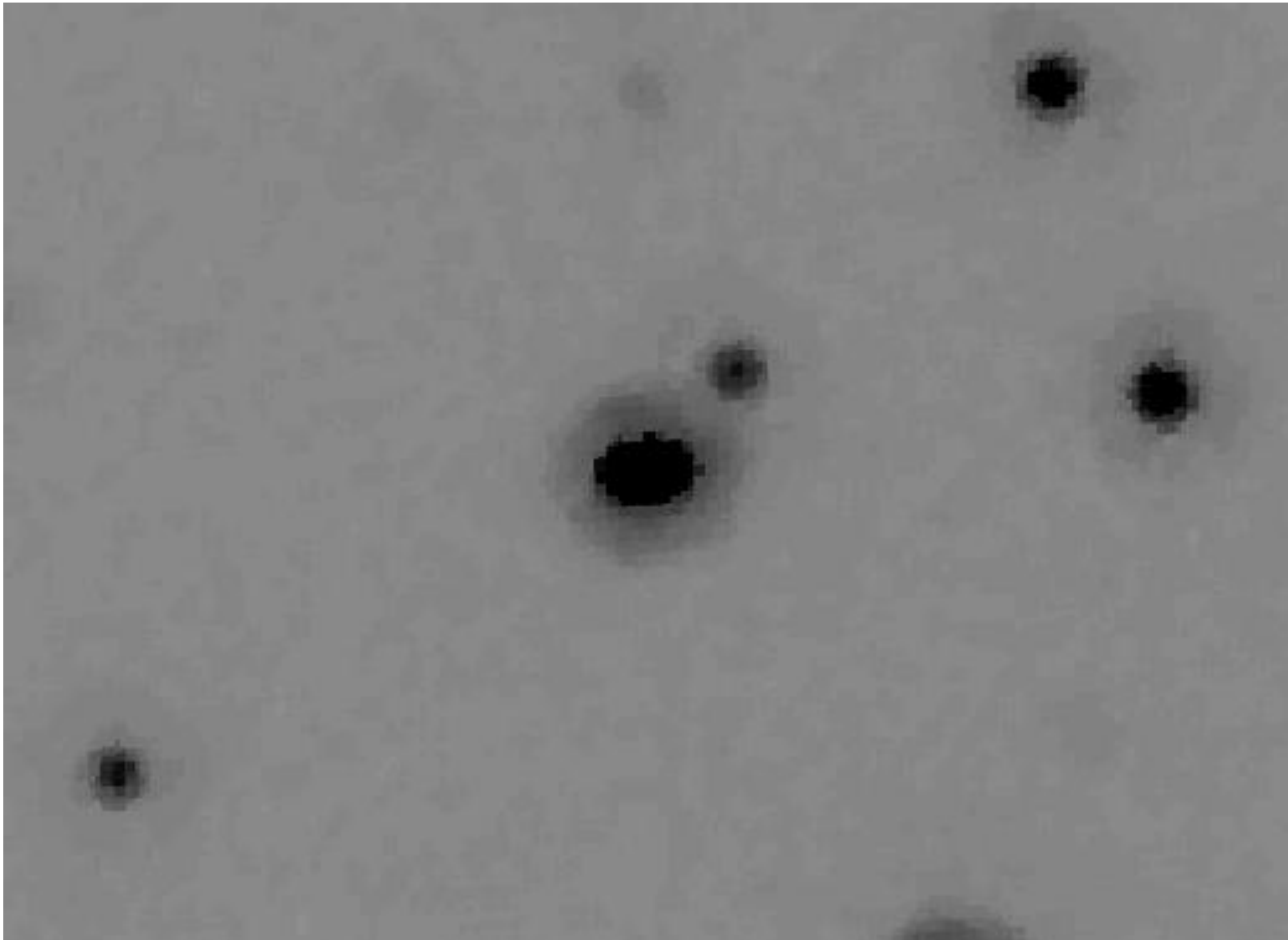


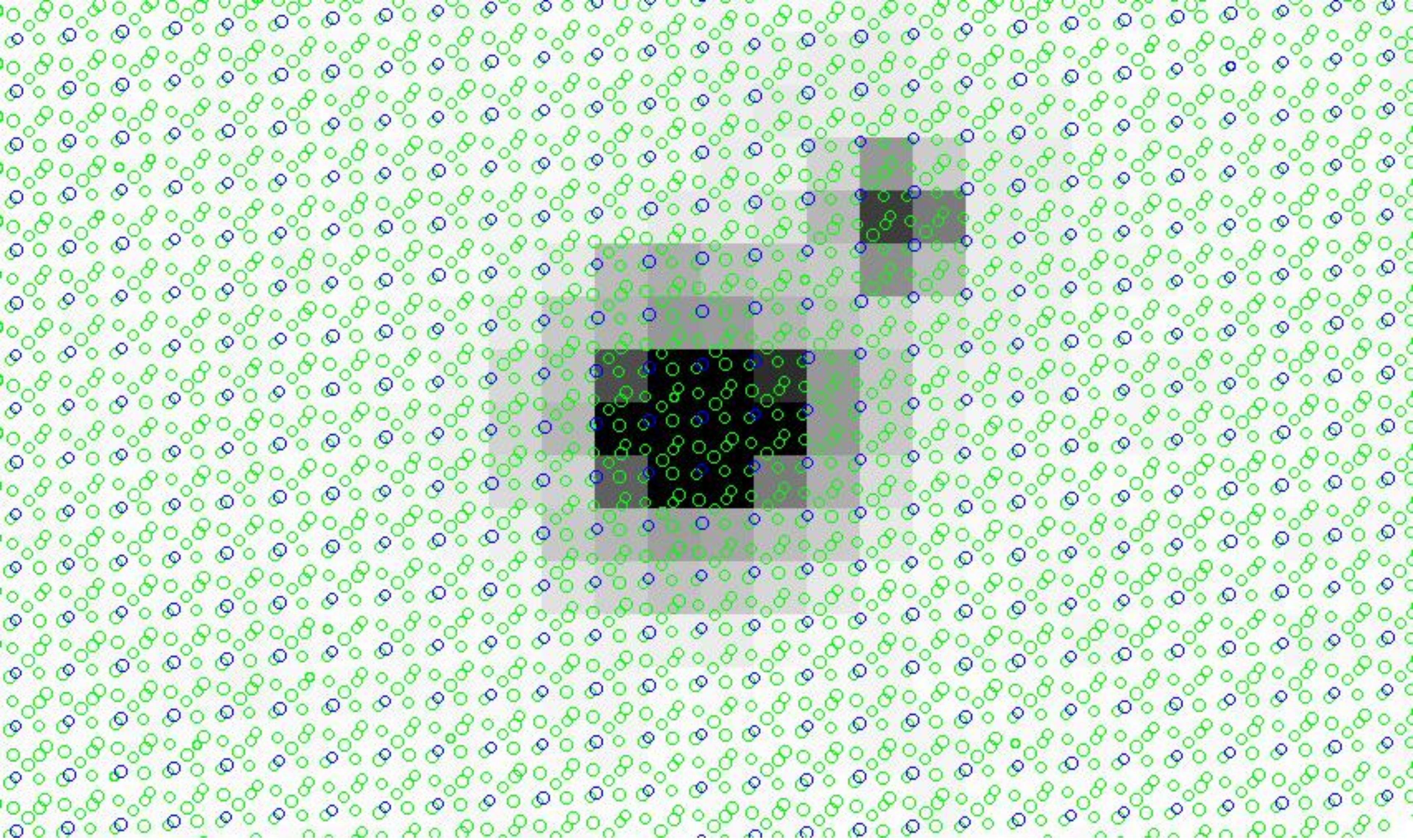
Stacked F814W Observations



Zoomed F814W Stack

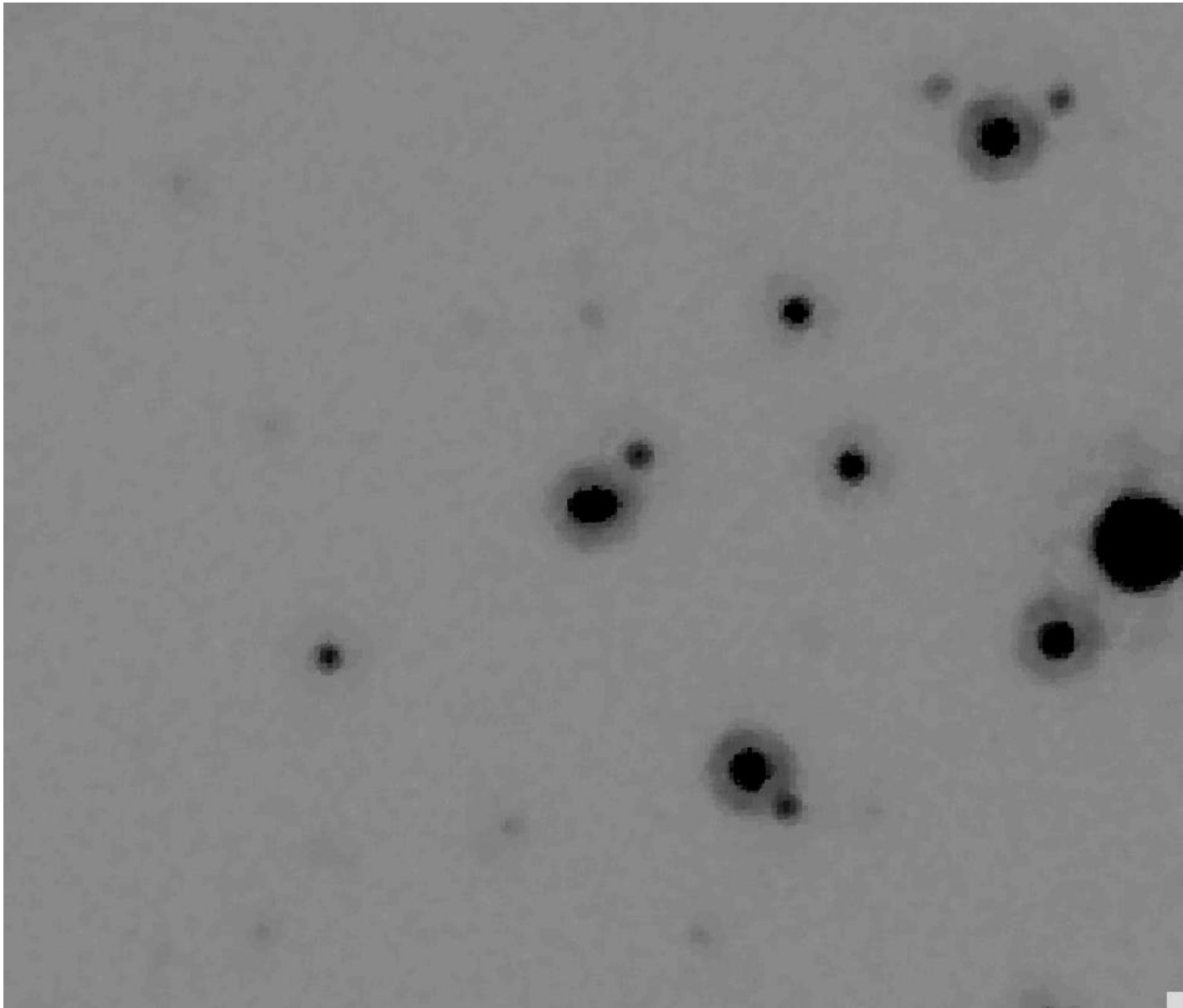
Source *looks* elongated relative to neighbors





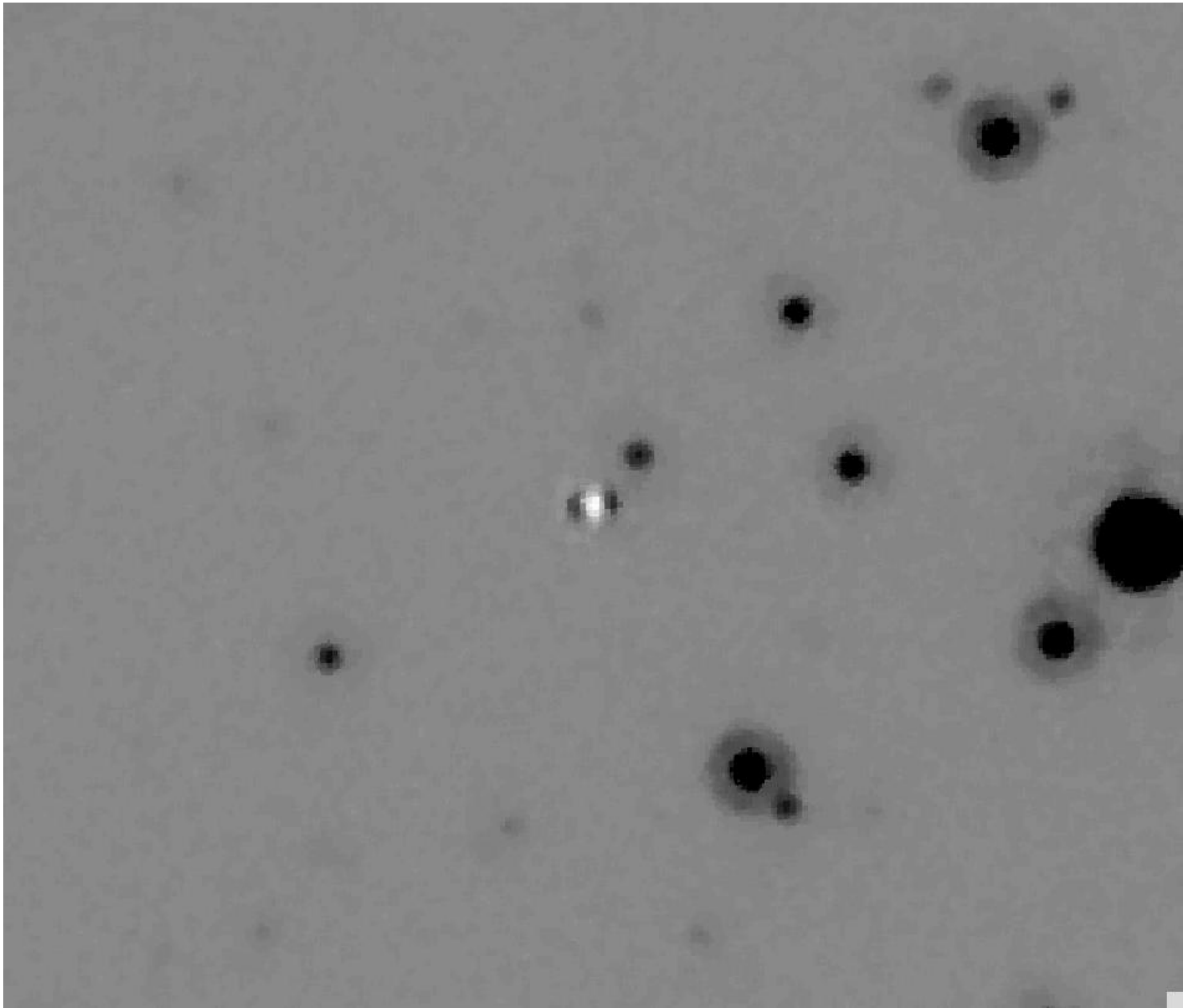
Achieved sub-pixel sampling

Stacked F814W Observations



Subtracted F814W Stack

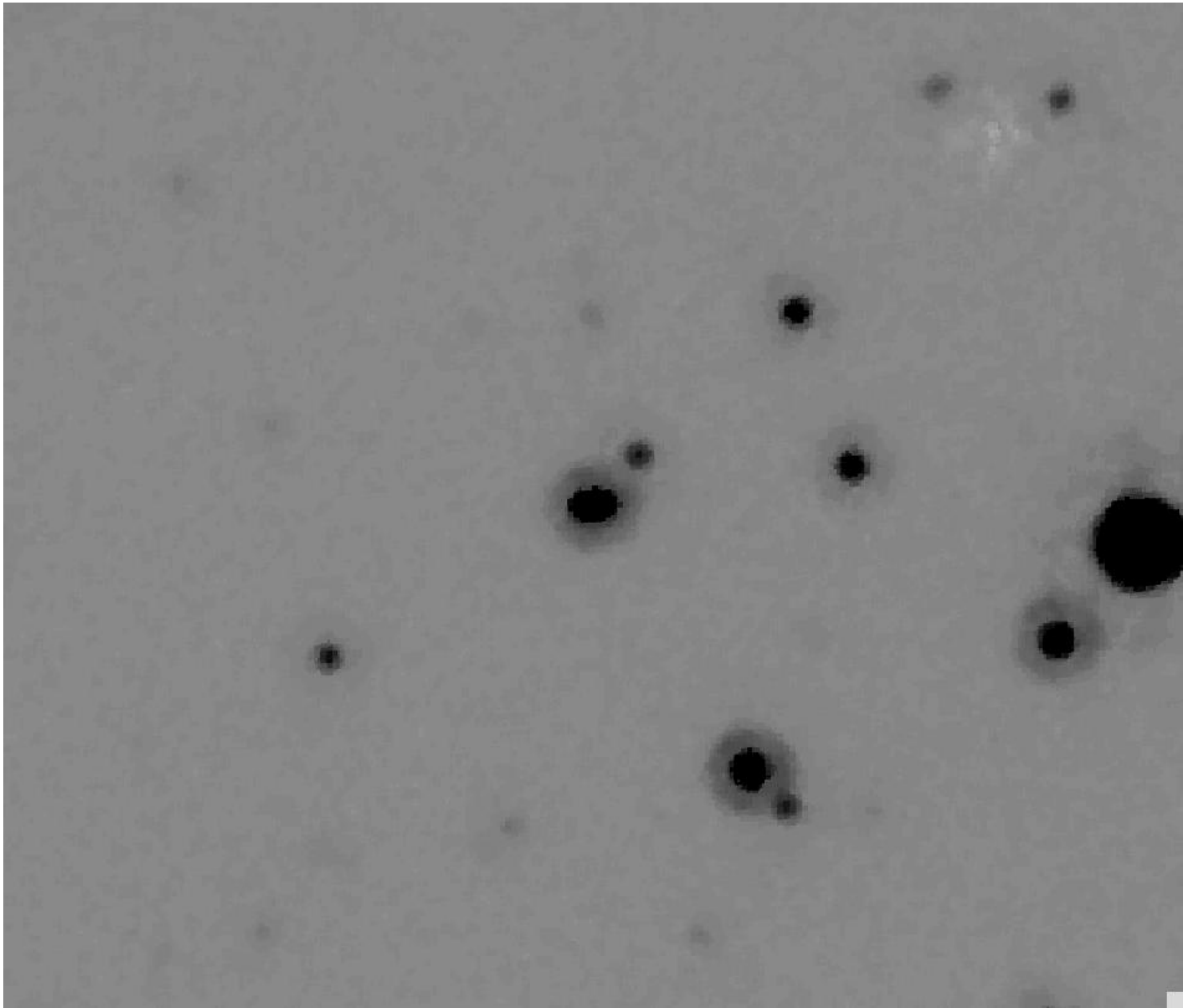
Residuals in X when we subtract a PSF from each image and stack…



Subtracted Neighbor…

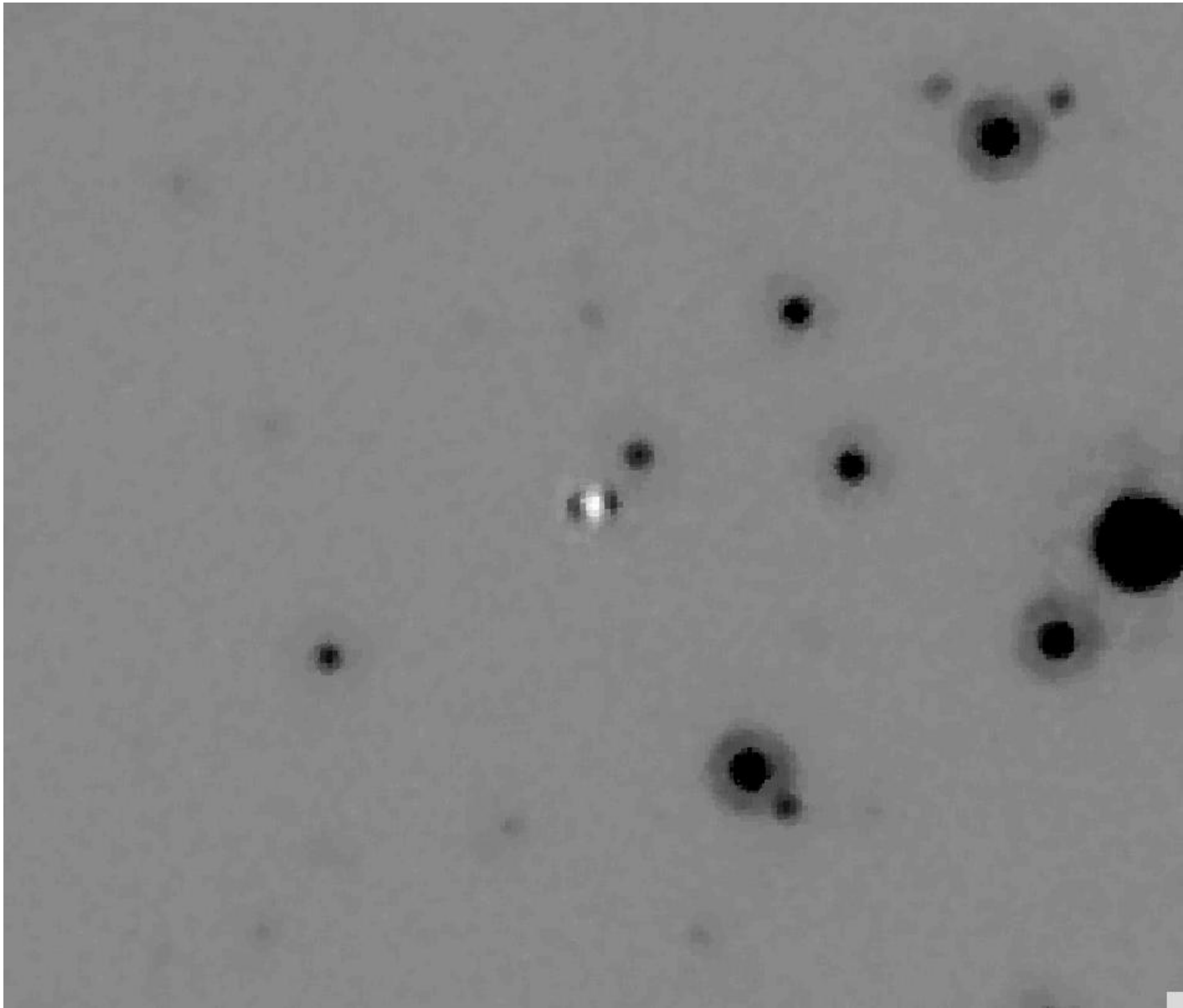
PSF IS GOOD!

Almost *no* residuals When we Subtract a PSF from a (brighter) neighbor



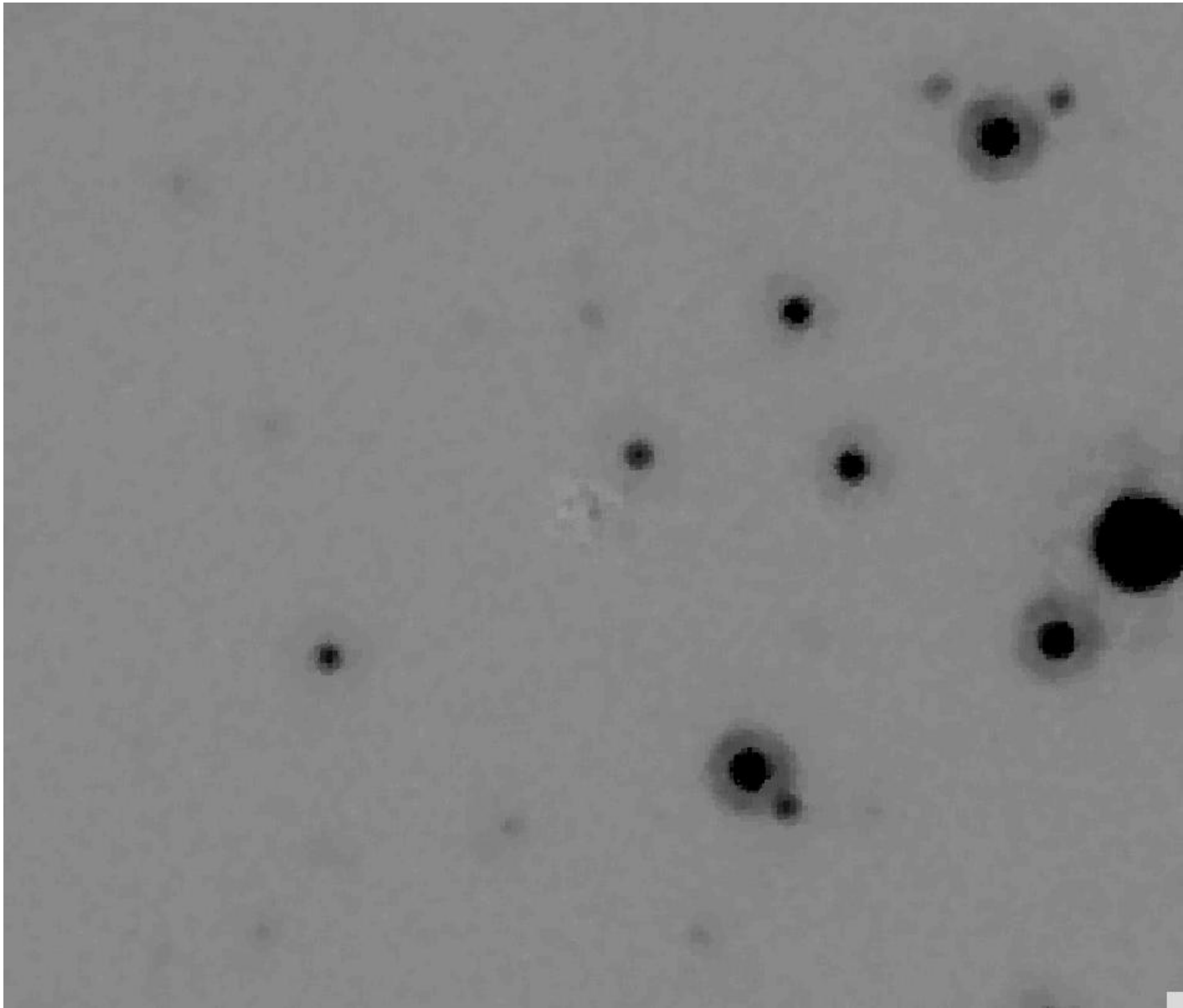
Subtracted F814W Stack

This means that the residuals of the target-star subtraction are *real*.



2-Source Subtracted F814W

We get very good subtraction residuals when we fit for *two* sources

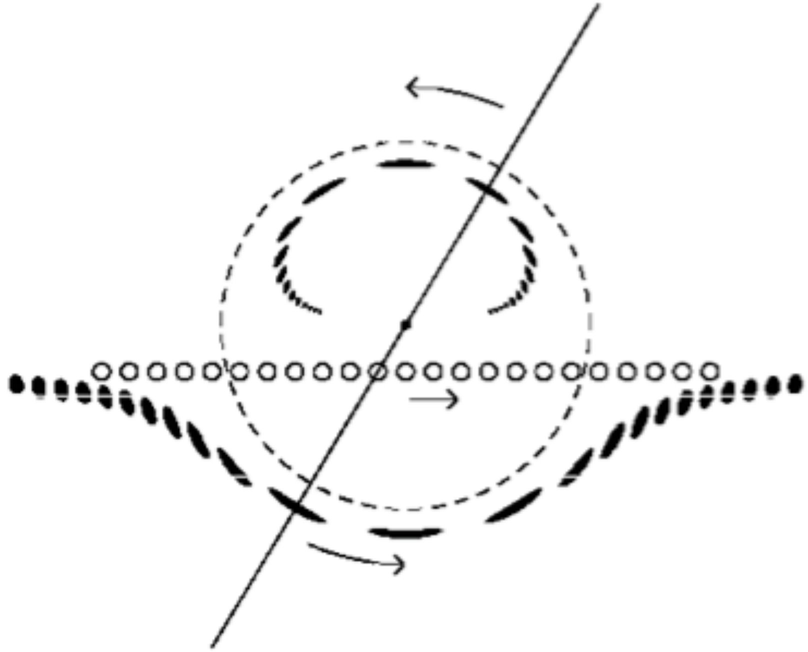


Two-source solution:

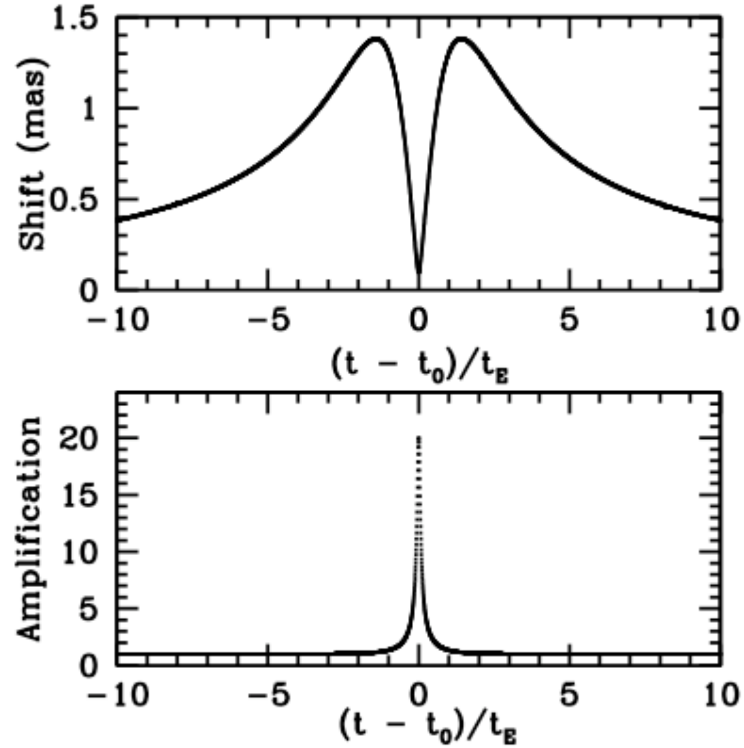
- Offset consistent in the B, V and I data:
  - Δx = 1.25 pixels = 50 mas (ΔT = 6 yrs)
  - Δy = 0.25 pixel = 10 mas
  - FLUX: (**left**) (**right**)
    - F814W 3392 e^- 3276 e^-
    - F555W 2158 e^- 3985 e^-
    - F438W 338 e^- 1029 e^-

3) Astrometry during the event

- Long-duration events: BH? NS? WD? BD?
- Kailash Sahu (PI)
  - Some long-duration event follow ups with HST
    - OGLE-2007-BLG-224
    - MOA-2009-BLG-260
    - MOA-2010-BLG-235
    - MOA-2010-BLG-356
    - MOA-2010-BLG-482
  - GO-12586: Finding our own events
    - 192 orbits over 3 cycles



Schematic of event

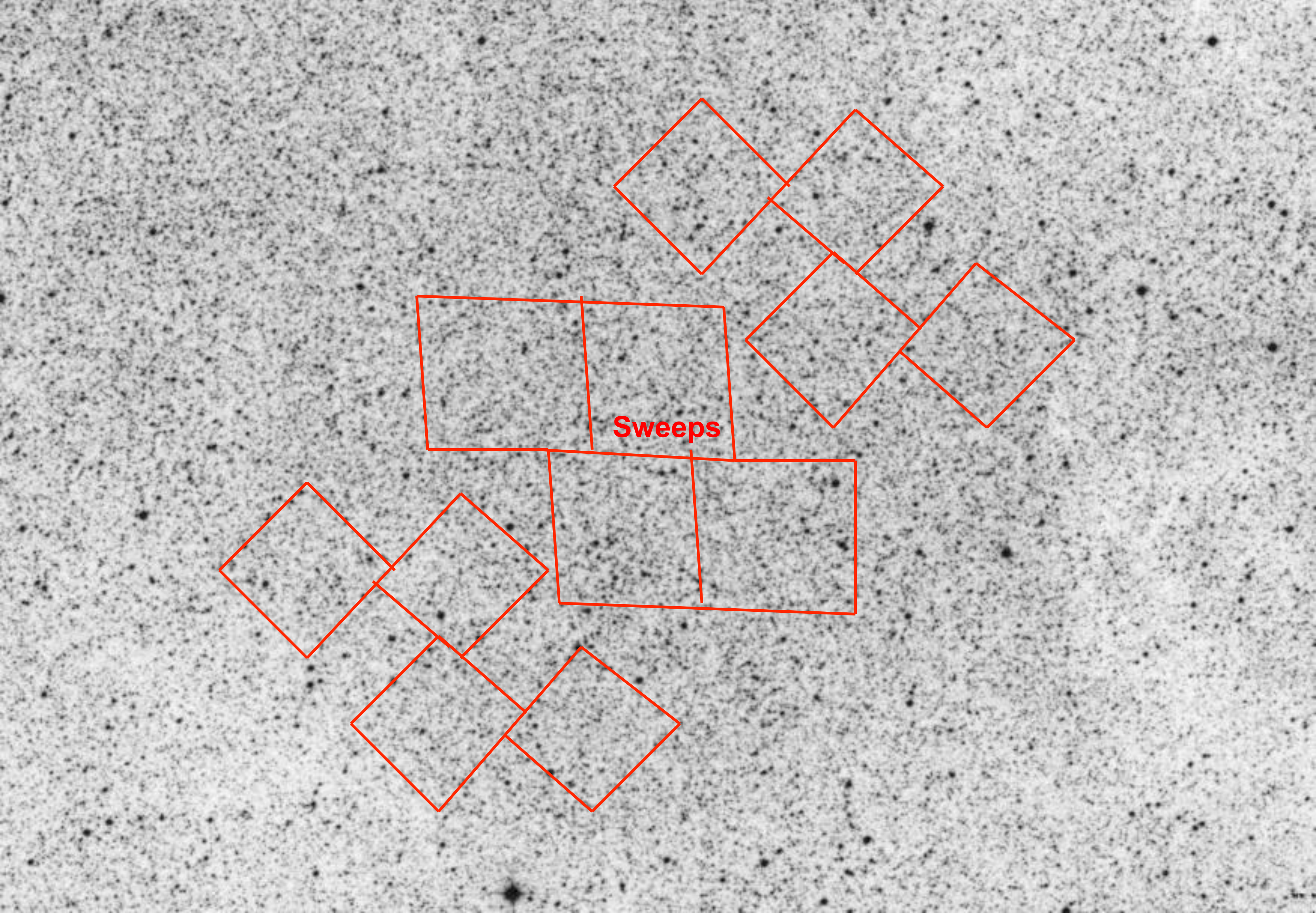


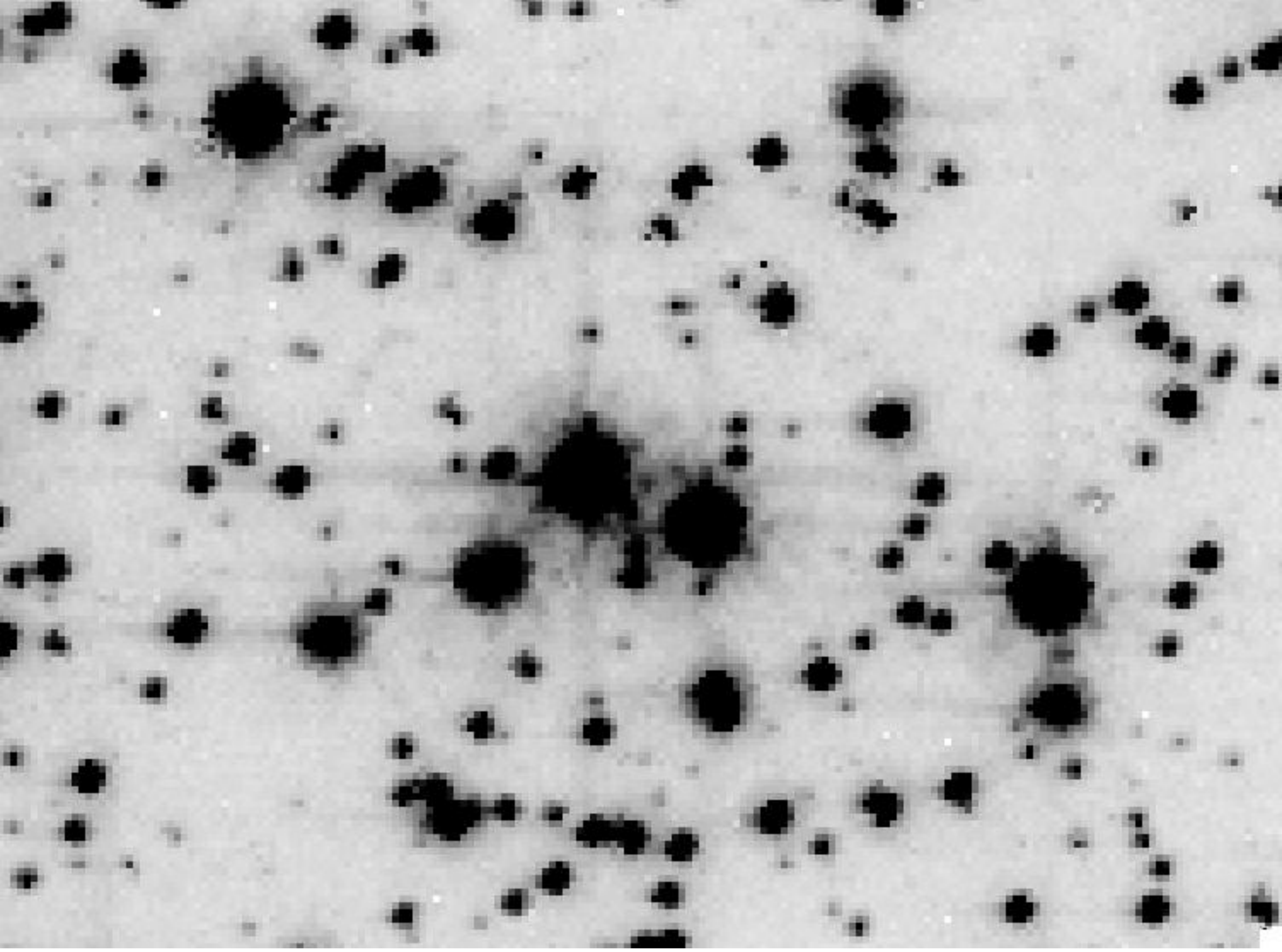
Photometry/Astrometry

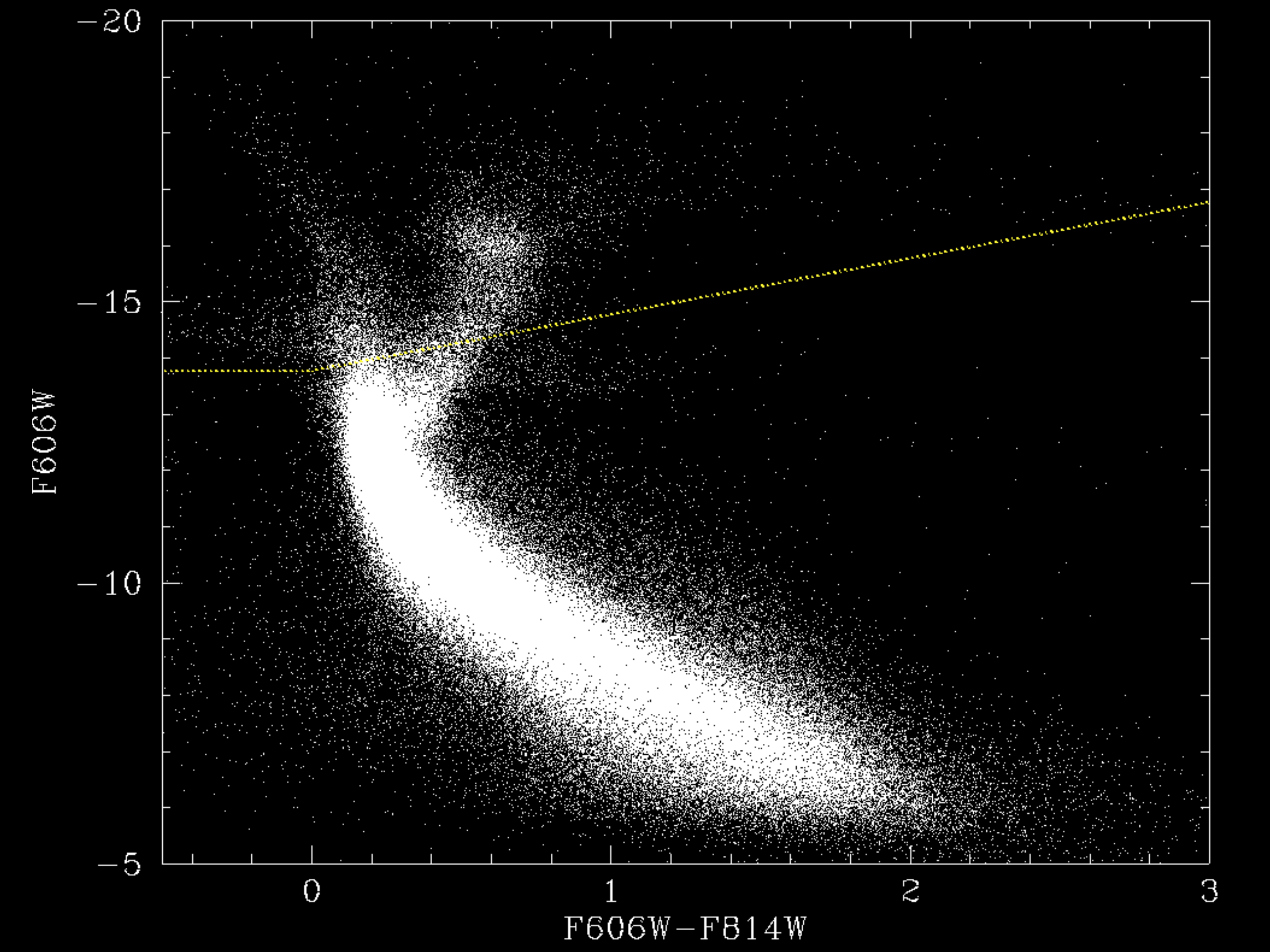
Duration of event $\propto$ mass $\times$ μ

Astrometric offset $\propto$ mass

Fast BH, NS, WD or slow BD?


Sweeps





−20
−15
−10
−5
0
1
2
3
F606W
F606W−F814W

OBSERVING STRATEGY

- **NUMBER OF TARGETS**
  - Each ACS field has ~200,000 stars
    - 50% have S/N > 100
  - Each WFC3/UVIS field has 150,000 stars
  - **Total of > 1,500,000 stars**
- **OBSERVING CADENCE**
  - Optimized for long-duration events
  - One visit every 2 weeks over two 4-month windows
    - 64 visits per year
- **EXPECTATIONS**: (54 / 120 events "astrometric")
  - 18 events due to BHs
  - 14 due to NSs
  - 22 due to MS stars…. **STARTS IN APRIL!**

APPLICATIONS TO WFIRST

- HST programs: hard to get time!
  - WFIRST will do for all sources
- Success with HST PSF encouraging
  - Model static part
  - Perturb with time-variable part
  - Need “semi-crowded” star field
    - Construct basis functions for PSF / GC
    - Long stare
    - WL will ❤ μL!
  - Demo software (Sahu program)

Omega Cen: a Ground-Based Image (Lehman)

GB → ACS → UVIS → PMs