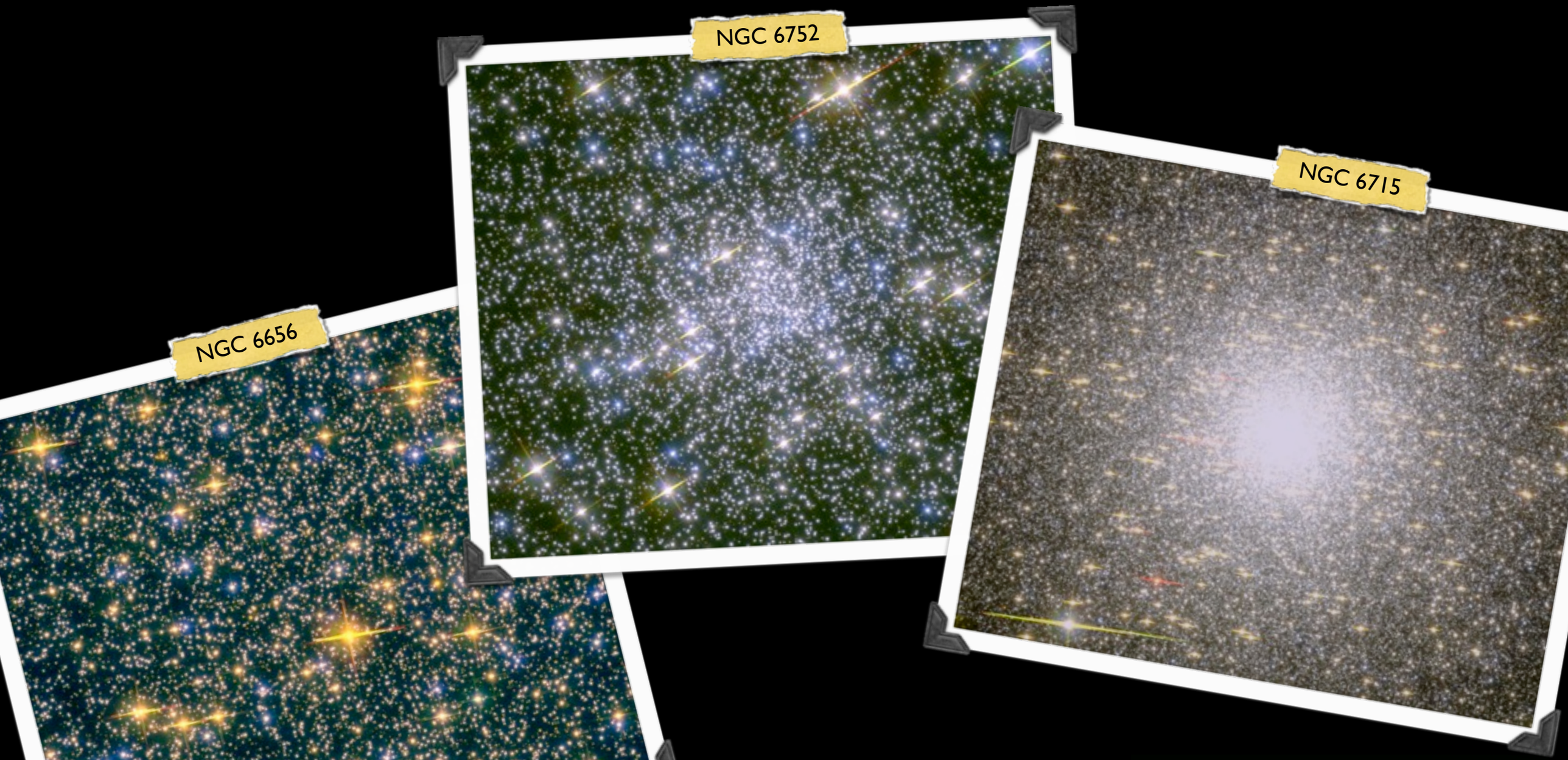
HST Proper Motions of Globular Clusters



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Jay Anderson
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Operated for NASA by AURA

Introduction

Part I: astrometry with *HST*
- undersampling
- geometric distortion
- differential nature

Part II: proper motions of globular clusters with HST
- what we can do with them

Part III: our project
- the catalog
- preliminary results

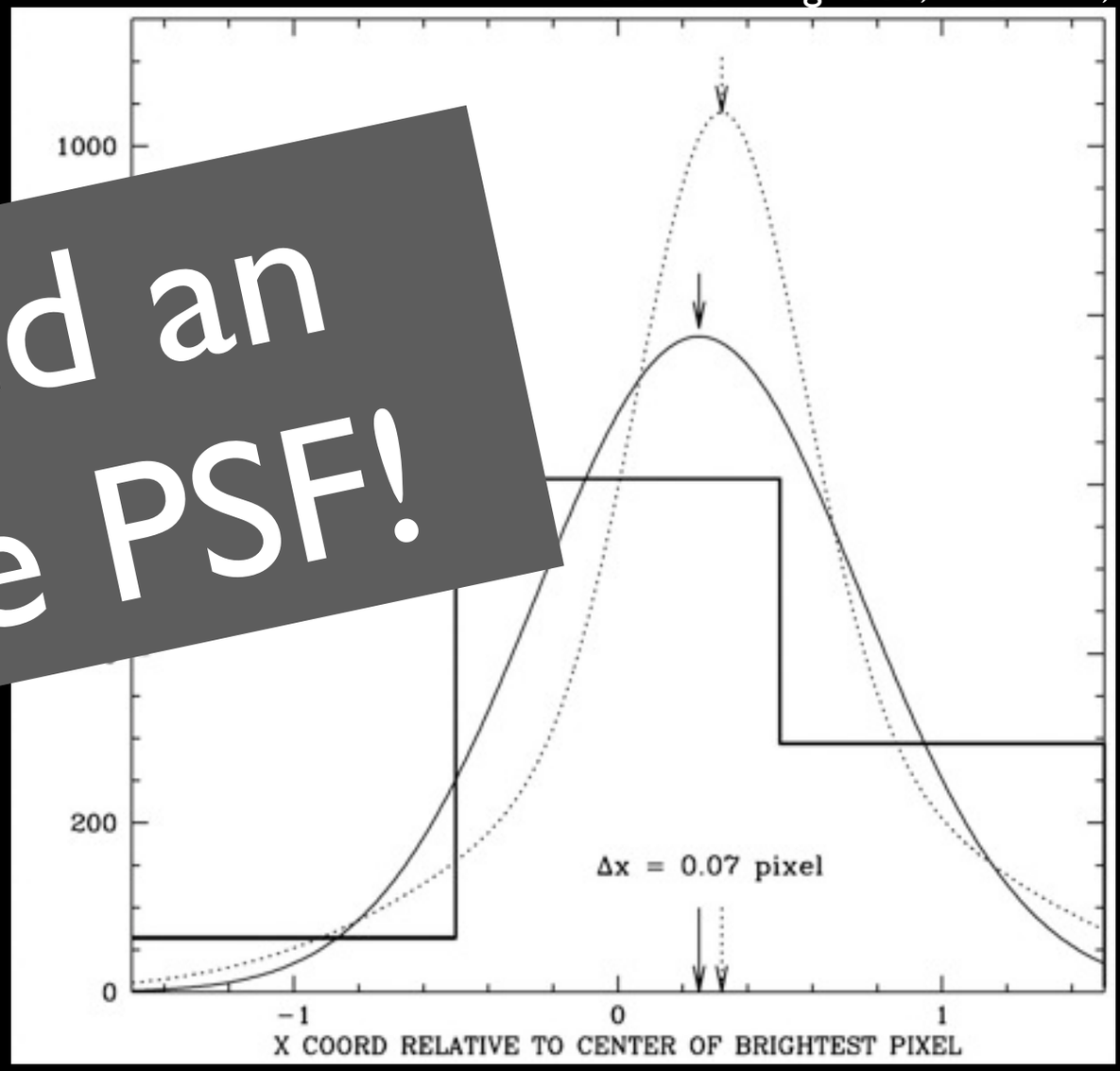
ISSUES#1: Undersampling

Illustration of Undersampling conditions

Where is the center?

We need an accurate PSF!

Anderson & King 2000, PASP 112,



Undersampling and Astrometry

Impossible?

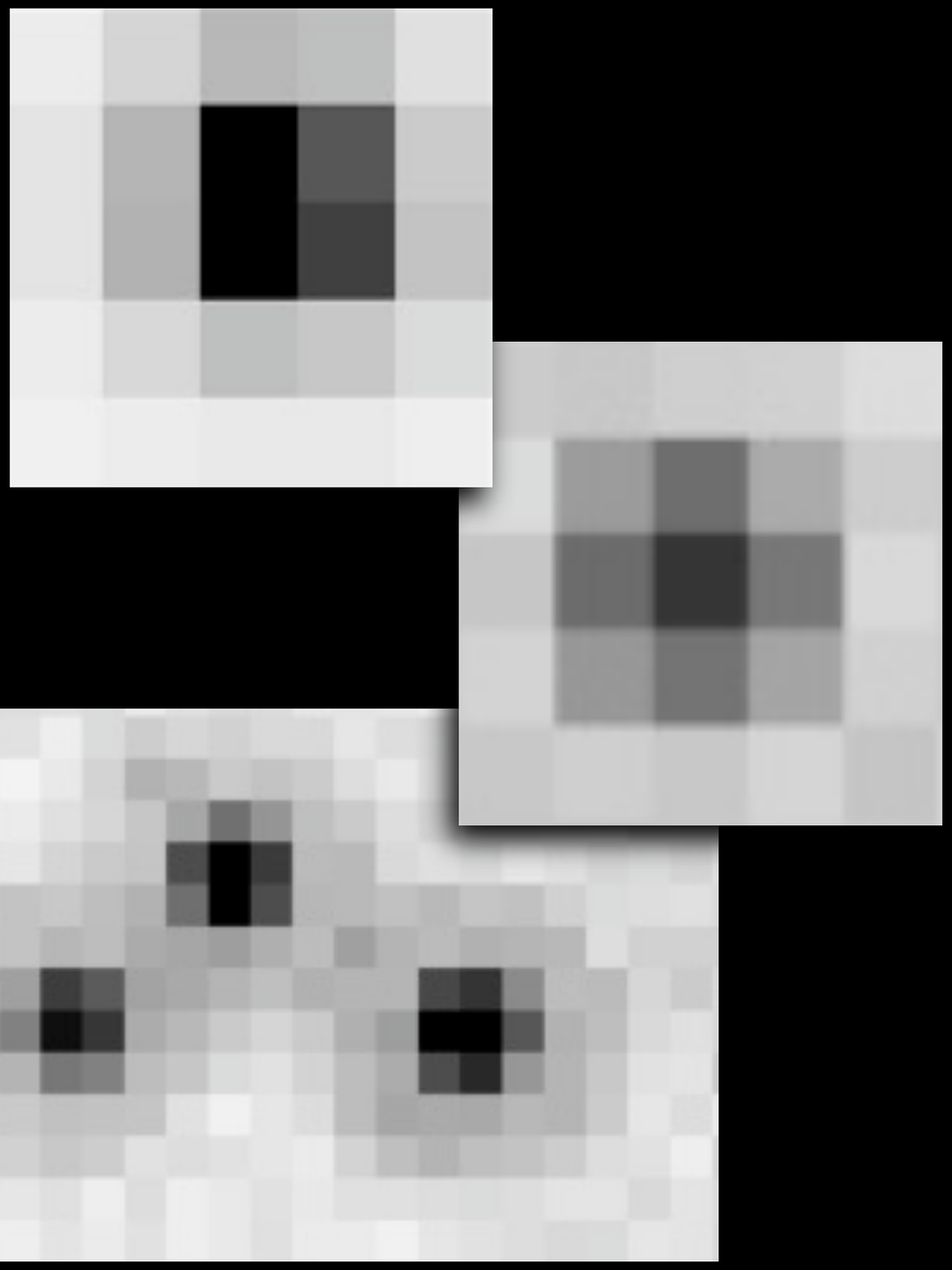
– A point source has "no hair"
  - 3 parameters (x_*,y_*,f), ~9 pixels
– Minimal requirements: "slosh"

What is possible?

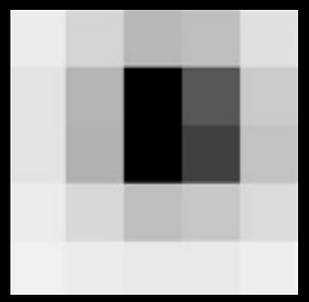
– ≲0.01 pixel possible ~ $(S/N)^{-1}$
  - Need good PSF model
  - Need good dithering

Limitations

– Individual images; no stacks
– Hard in crowded fields
  - Neighbor finding/subtraction
– Ideal in "semi-crowded" regime



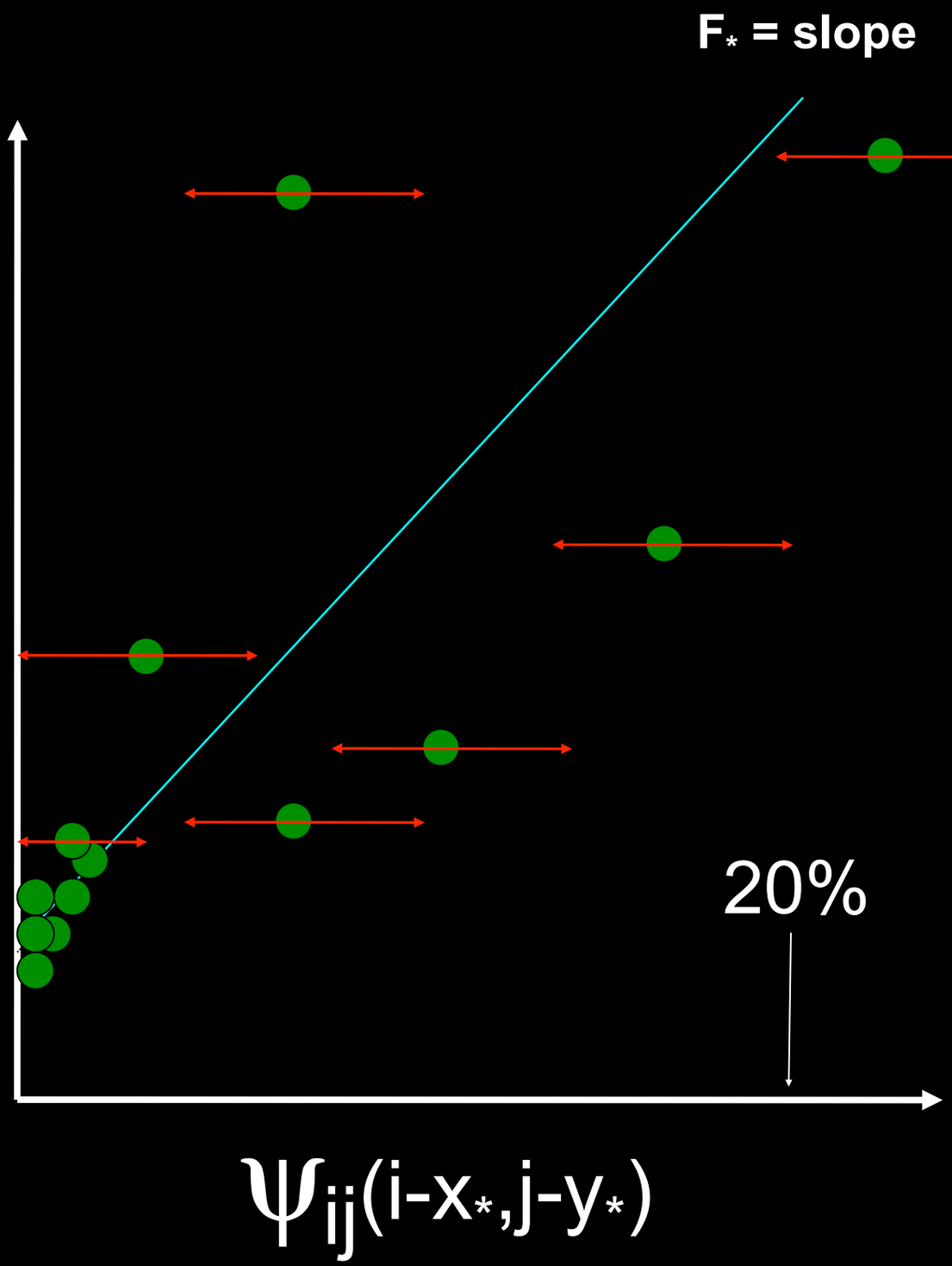
How to use the PSF:



Fitting for Flux and position:

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

- Nice, linear equation!
  - P in S_*, F_*, not (x_*,y_*)
- Sky from outer annulus
- For given (x_*,y_*), get $F_*=\Sigma(P_{ij}-s)/\Psi_{ij}$
- Find optimal (x_*,y_*)



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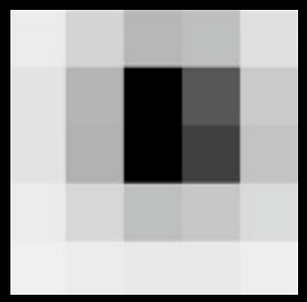

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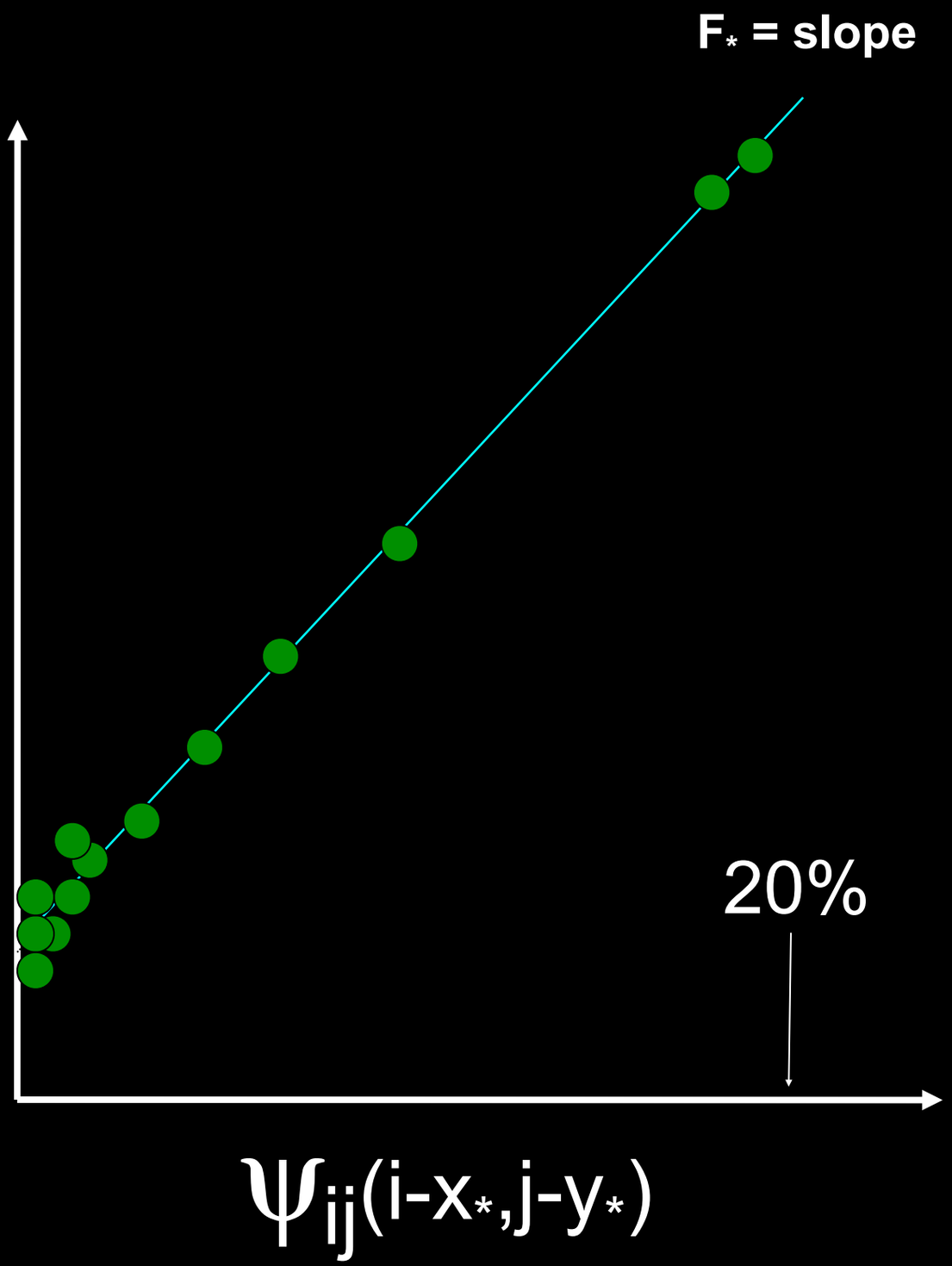
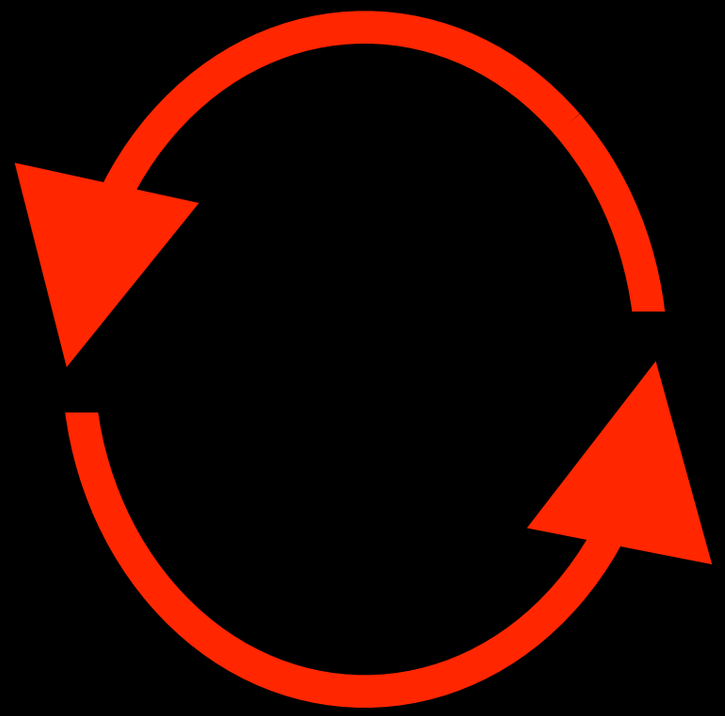


PSF: Finding vs. Using

- Degeneracy:
  - Finding Ψ_{EFF} requires (x_*,y_*,f)
  - Finding (x_*,y_*,f) requires Ψ_{EFF}

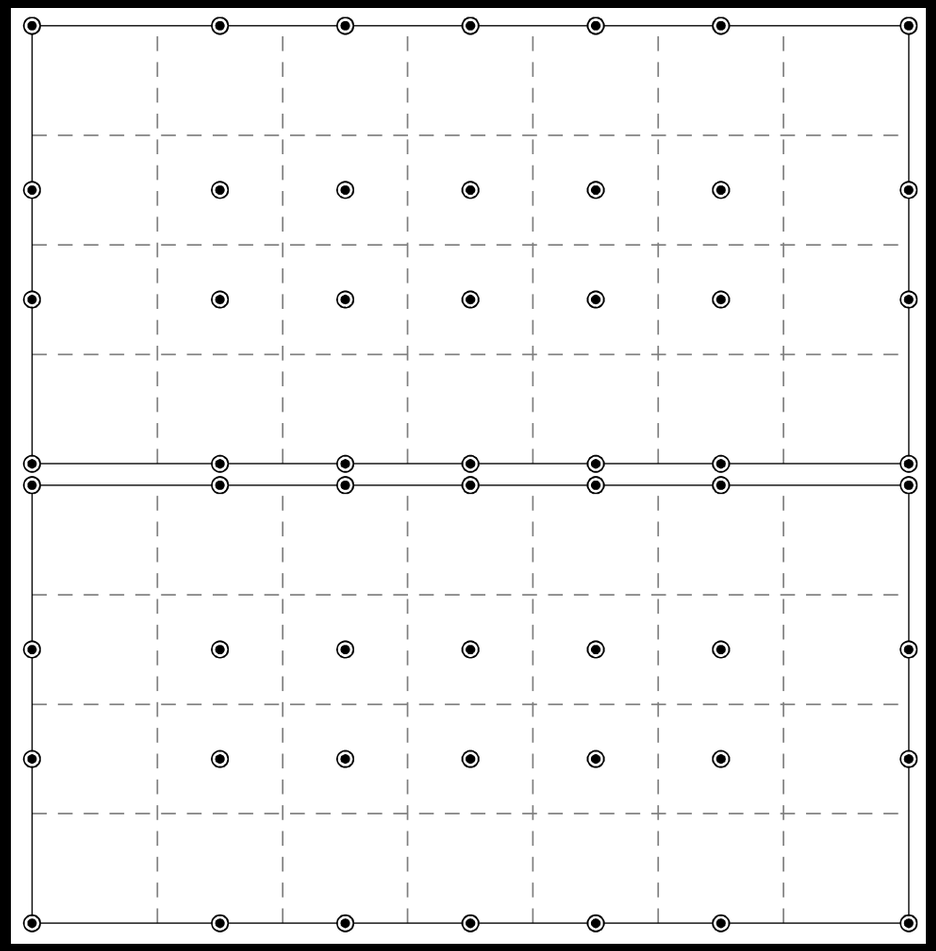


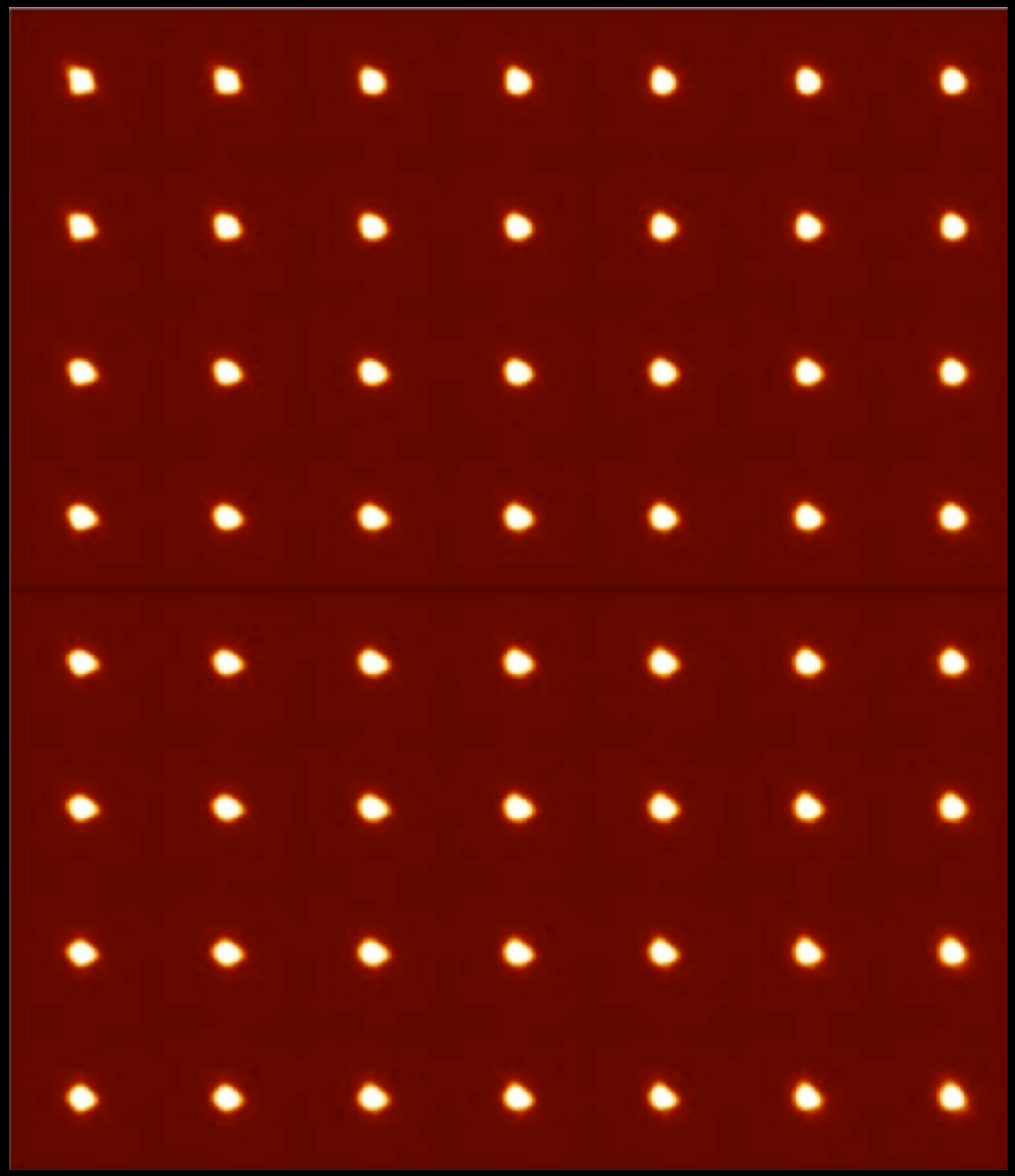
- Iteration
  - Dithers break the degeneracy!

Higher-level PSF issues:

- Spatial variability:

  2(7x4) PSF array for WFC3/UVIS F438W



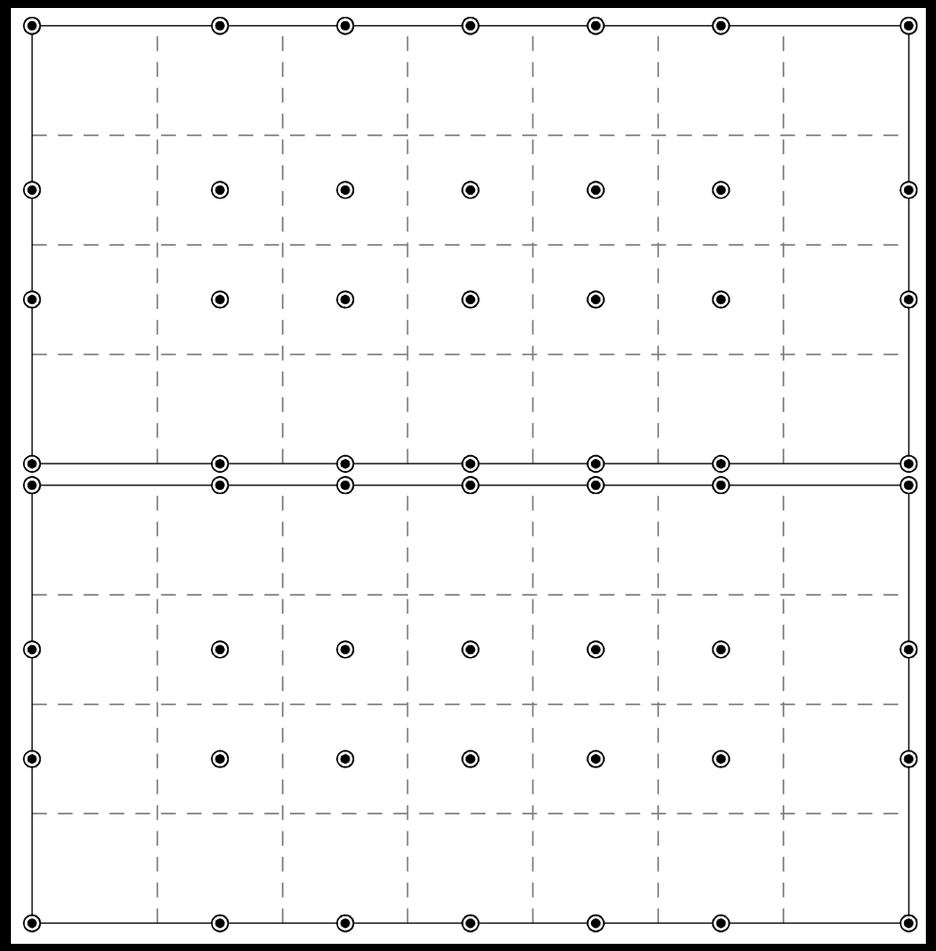


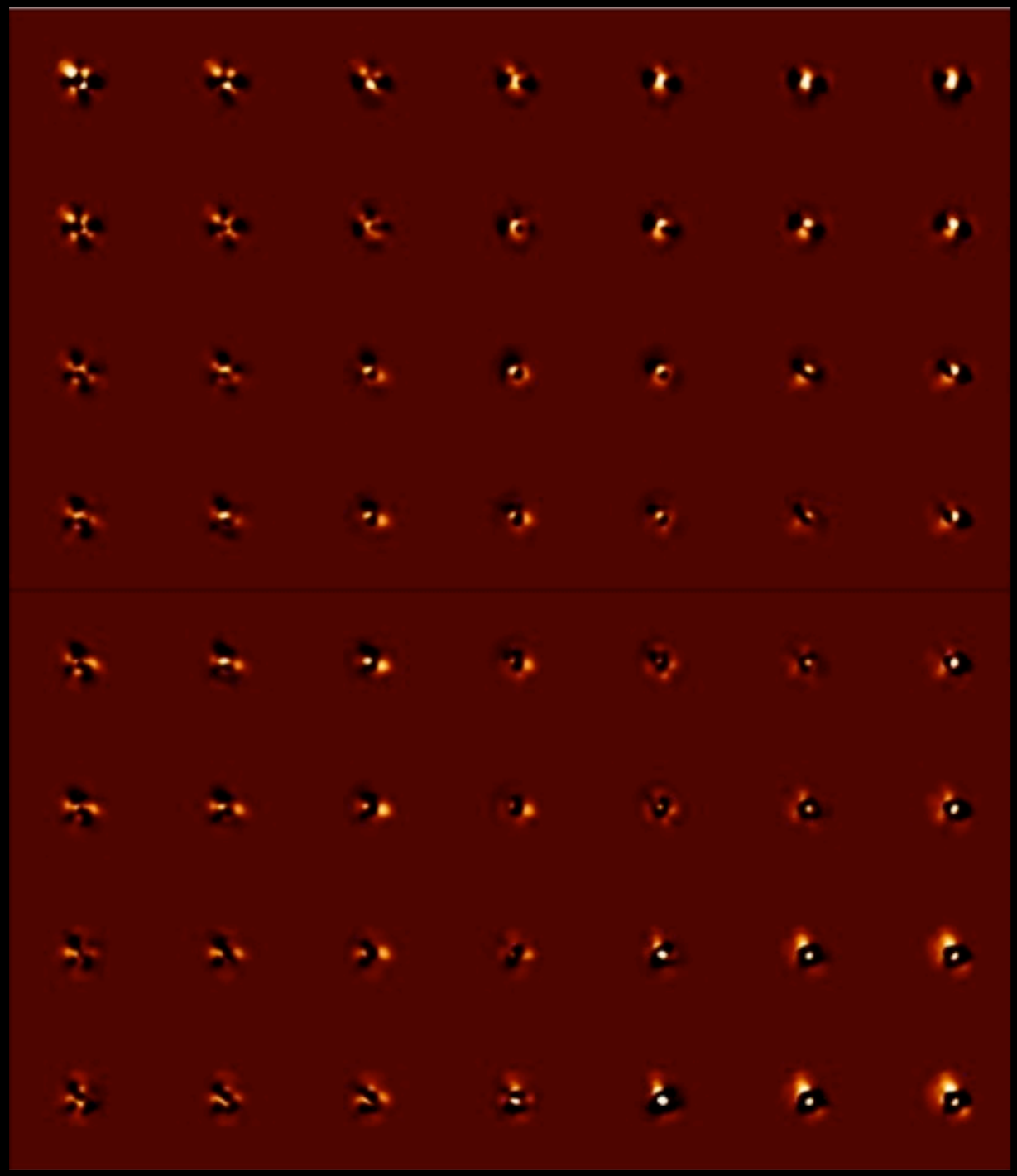
Higher-level PSF issues:

- Spatial variability:

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

- Time variability (breathing)





ISSUES#2: Geometric Distortion

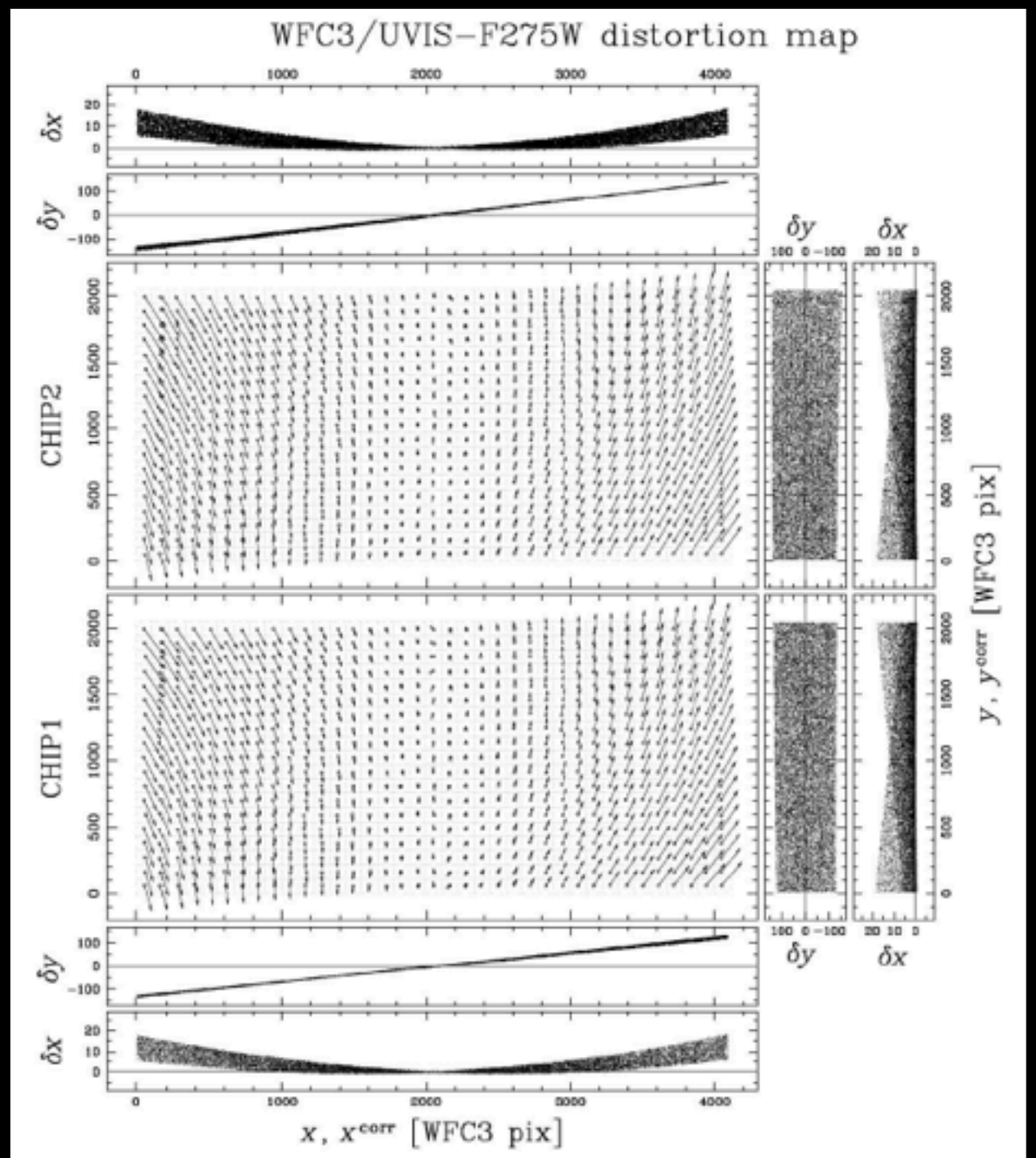
Why? Fewer reflections, better throughput

- Linear "skew": 500 pixels over 2000 px
  → Parallelogram pixels
- Non-linear: 50 pixels over 2000 px

- Filters introduce distortion (~0.1 pixel)
- Detector "stitching" defects
  - WFPC2: every 34.1333th row 3% shorter
  - ACS/WFC: pattern every 68.2666th column
  - WFC3/UVIS: 2-D zones
- CTE losses...
  - ACS Solution now available (WFC3 one on the way)

Need empirical approach: plot everything against everything else…

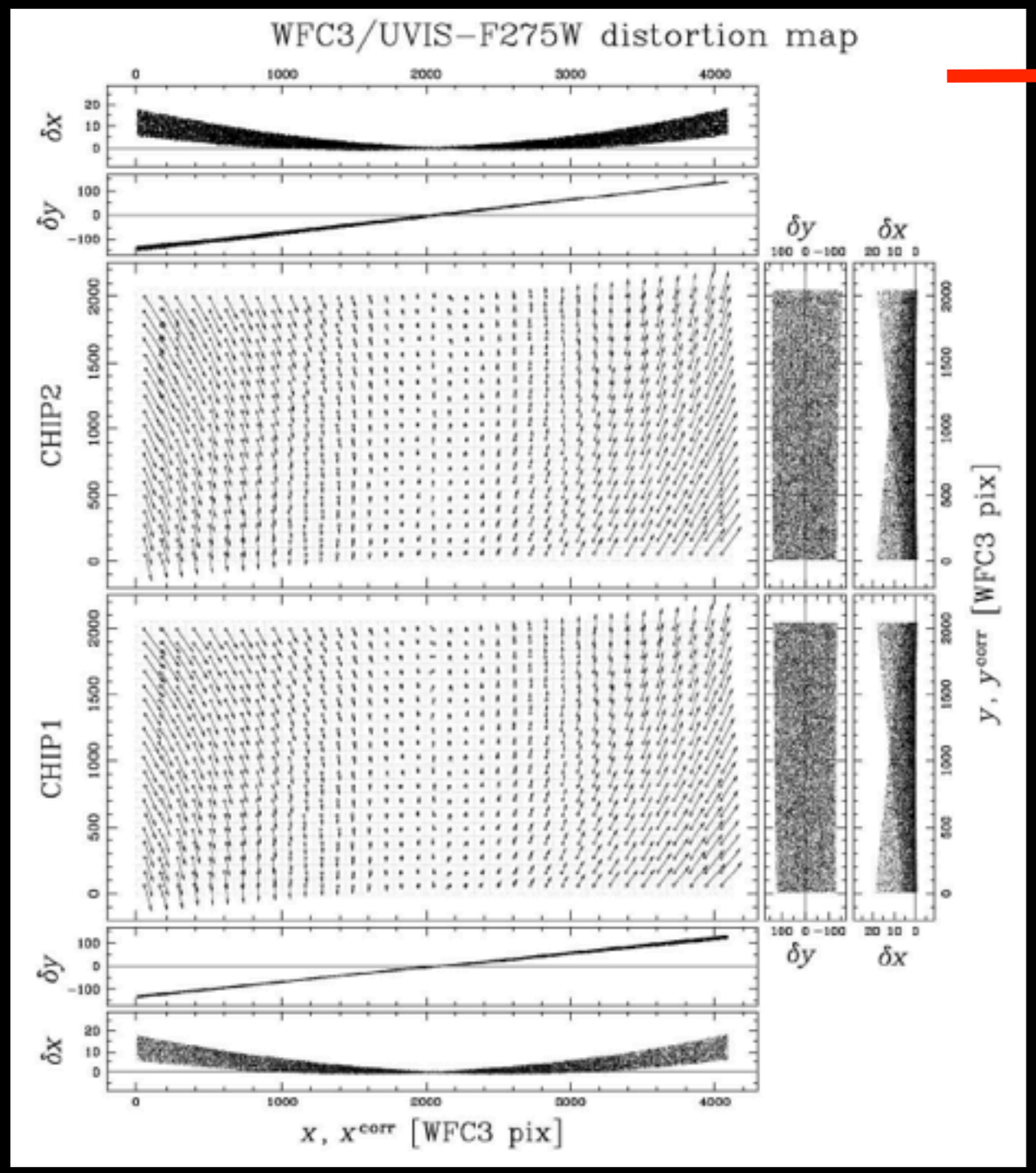
WFC3/UVIS Geometric-Distortion Correction



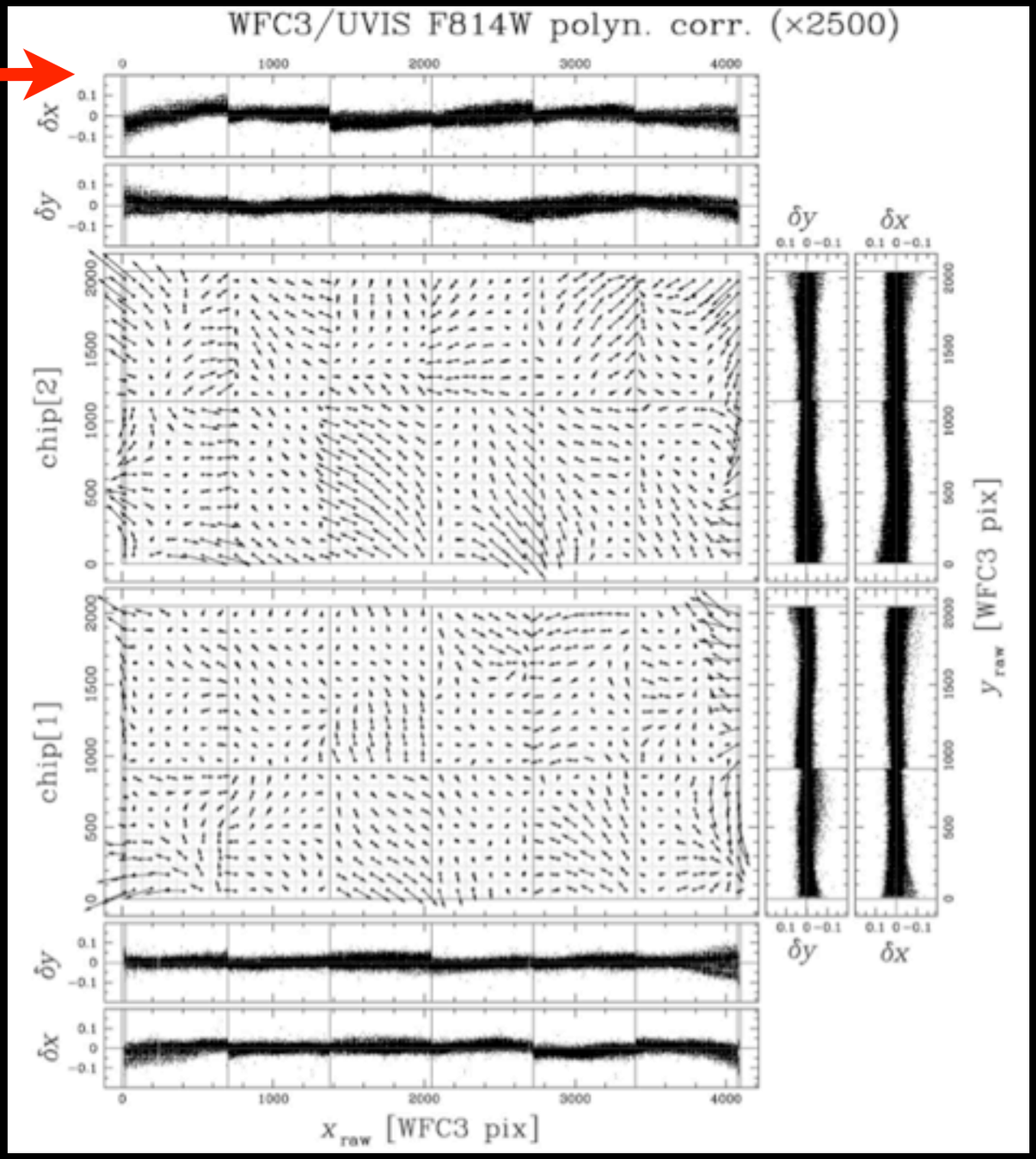
Bellini & Bedin 2009, PASP, 121, 1419

WFC3/UVIS Geometric-Distortion Correction

auto-calibration & polynomial solution



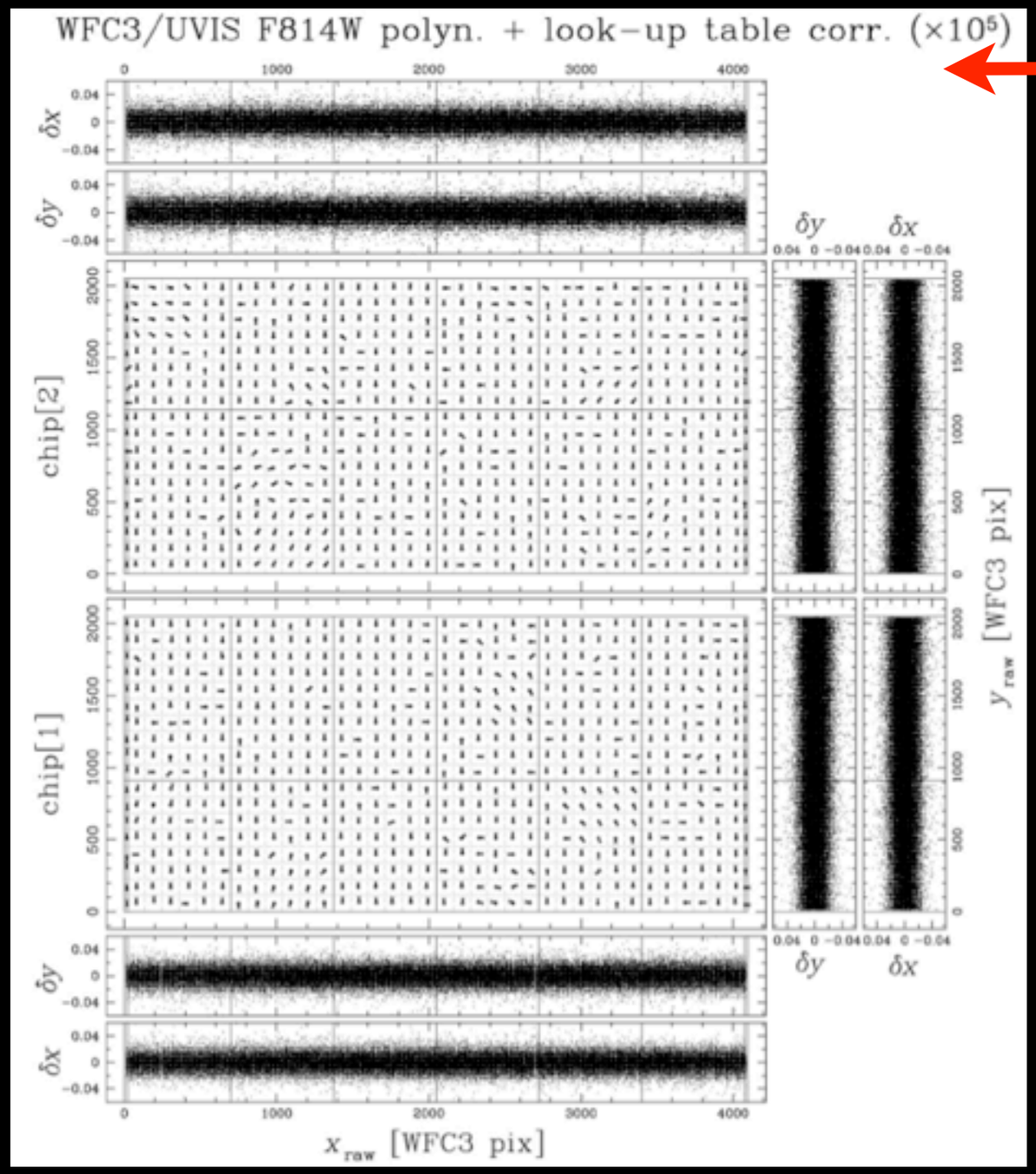
Bellini & Bedin 2009, PASP, 121, 1419

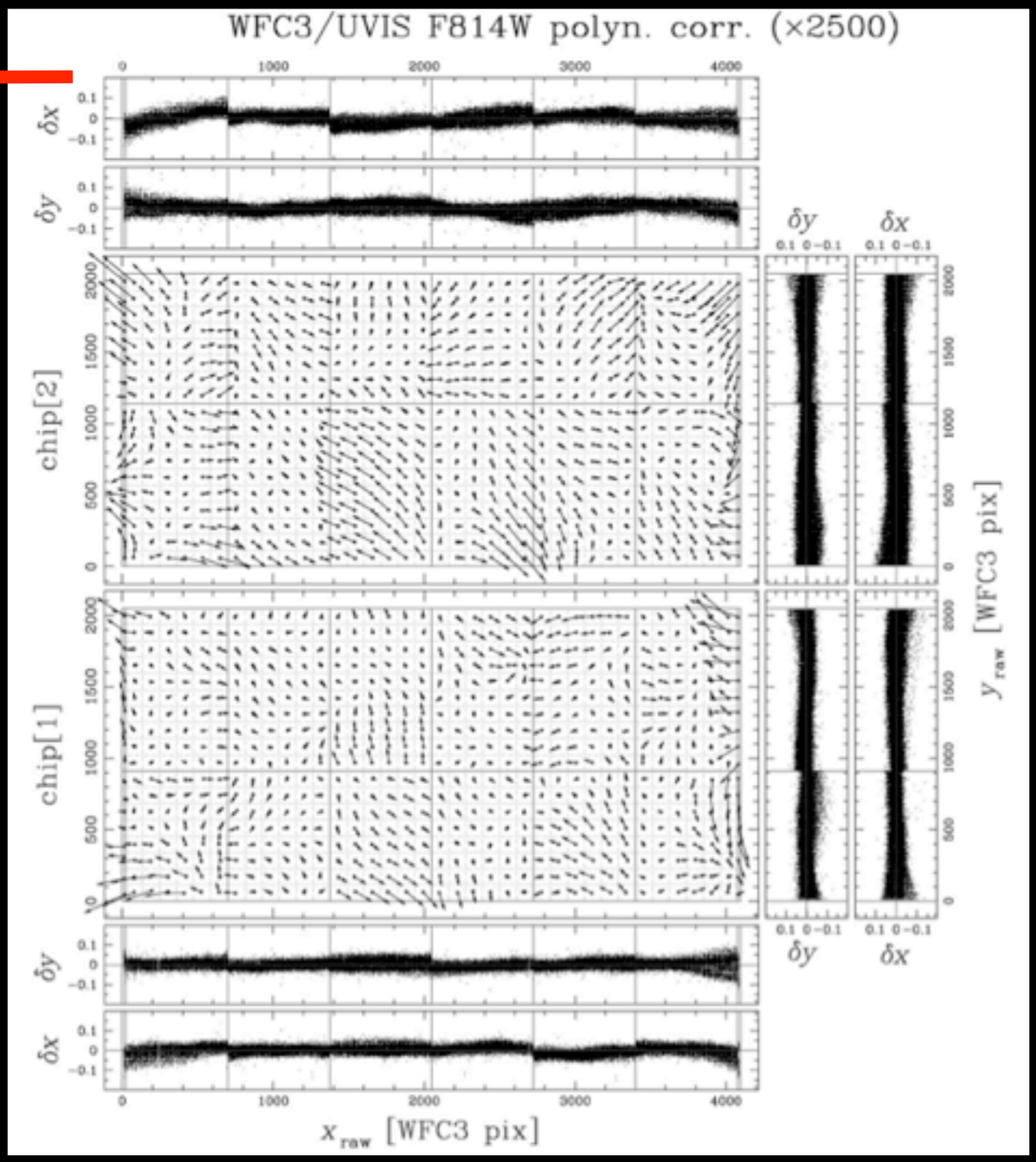


Bellini, Anderson & Bedin 2010, PASP, 123, 622

WFC3/UVIS Geometric-Distortion Correction

Table of residuals correction





Bellini, Anderson & Bedin 2010, PASP, 123, 622

Astrometric flat-field to the < 0.01-pixel level

ISSUES#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

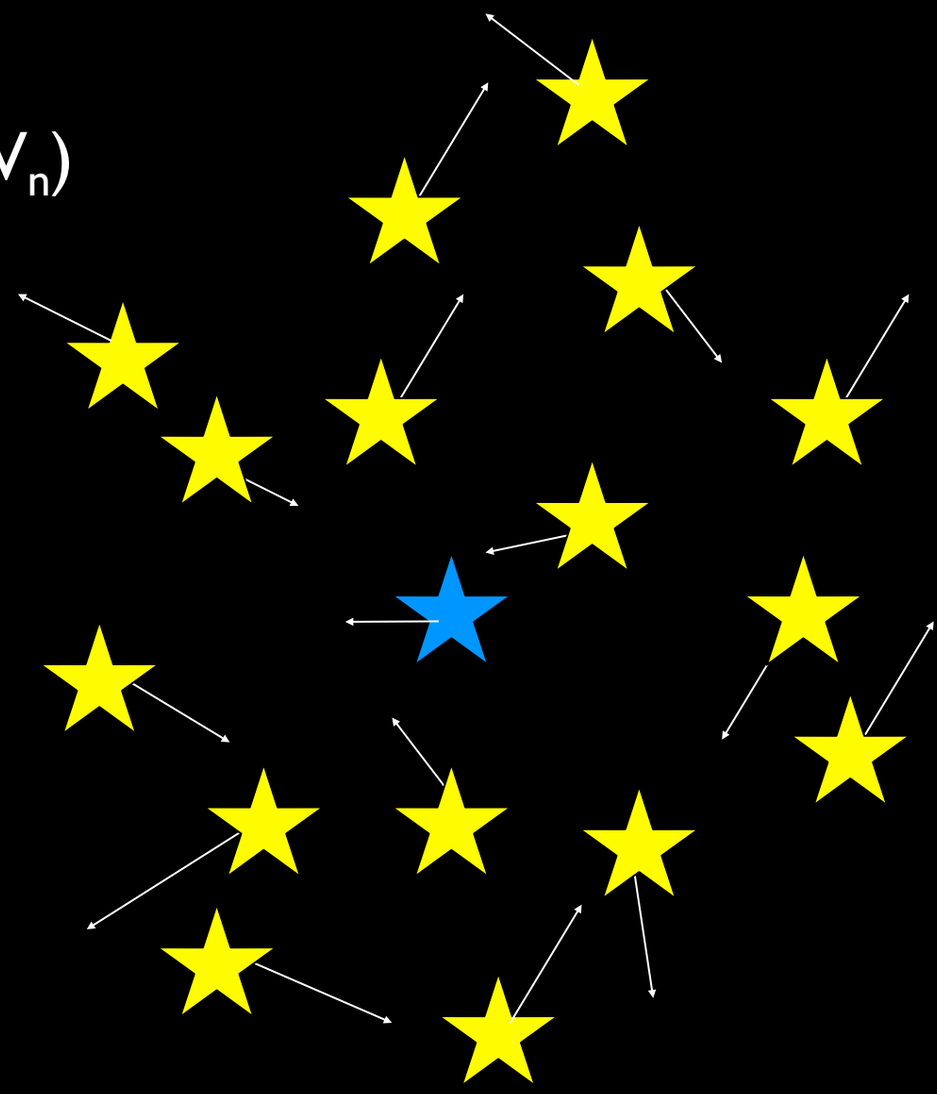
Always need to define a local reference frame

- Pixels/positions have only relative meaning
- Choosing a frame
  - * Base it on a population of objects (3+) in the frame
  - * Must know a priori something about the population
    - → absolute μ = 0 (galaxies)
    - → average μ = same (clusters)
    - → average μ = unchanging (field)

ISSUES#3: Transformations

Errors in the transformations:

- "Point" associations are not perfect: $(X_n, Y_n ; U_n, V_n)$
  - Stars' measurement error
  - Proper motions (dispersion)
  - "Fuzzy handles" for galaxies/faint stars
- Distortion not perfectly removed



Make transformations more local

$V_{SYST} = \sigma/\sqrt{N}$

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, models available, small variations, $\lesssim$ 0.01 pixel

Transformations:

- Can optimize for program

Bad news...: No one-size-fits-all solutions…

Science with HST proper motions

IMBHs

- Many advantages vs. Line-of-Sight veolicity studies
  - no spectra required (more/fainter stars, better statistics)
  - individual star measurements vs. integrated light
  - two components of velocity are measured (constrain velocity-dispersion anisotropy)
  - if LoS are known for some stars → 3D velocity dispersion anisotropy, better models (Schwatzchild)

GC dispersion profiles

- PMs for nearly all stars, especially in the concentrated central regions
  - better constrains of structure, dynamics, evolution of GCs

Geometric distances

GC rotations

Absolute motions

Microlensing applicantions

...

Courtesy by Jay Anderson

WFI → ACS → WFC3 → PM

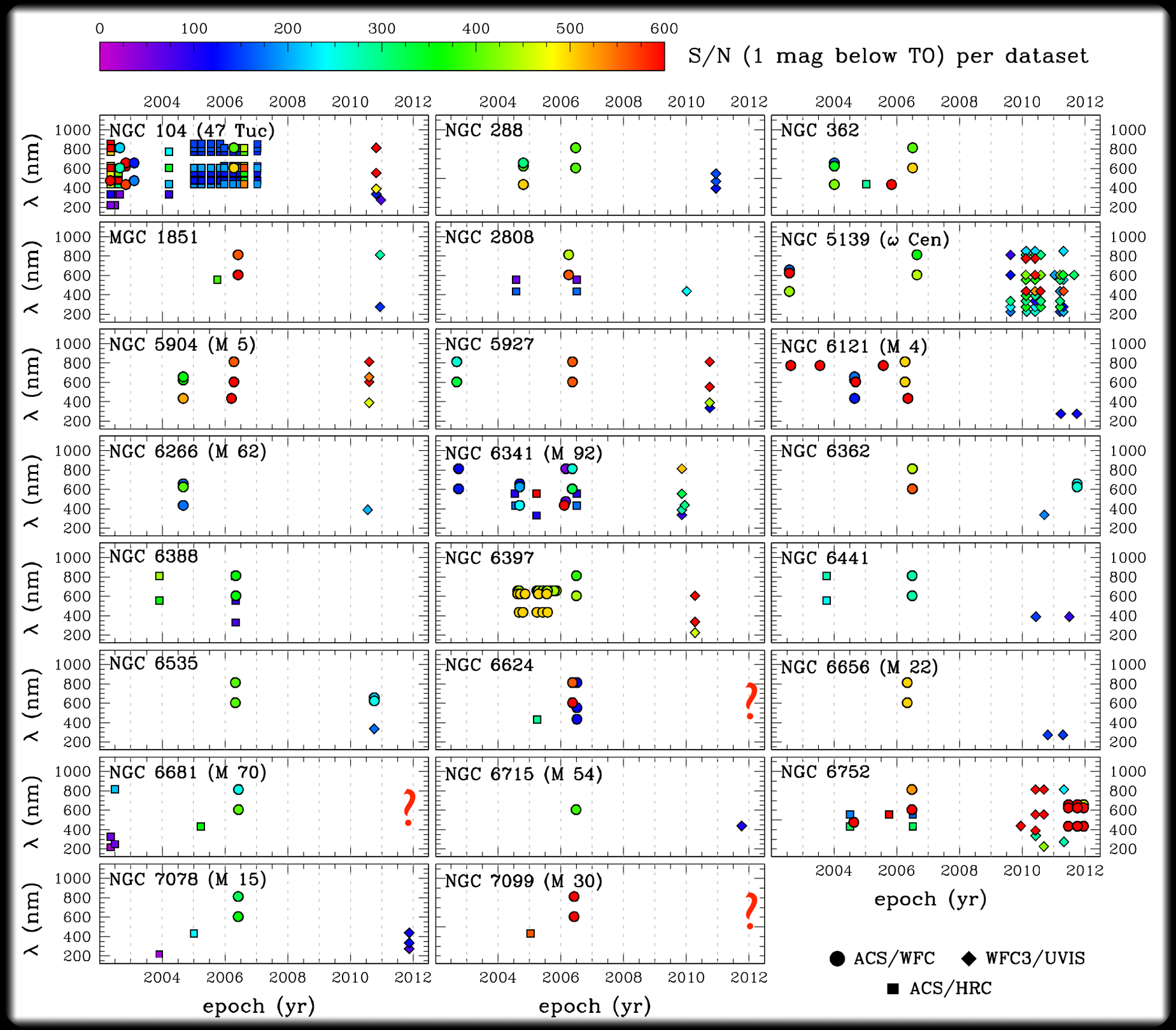
23 GCs:

5 (PI: Chandar)
4 (PI: Brown)
3 (PI: Ford)
1 (PI: van der Marel)
10 from HST archive

Heterogeneous datasets:

- different epoch coverage
- different cameras
- different filters
- different S/N

Homogeneus reduction



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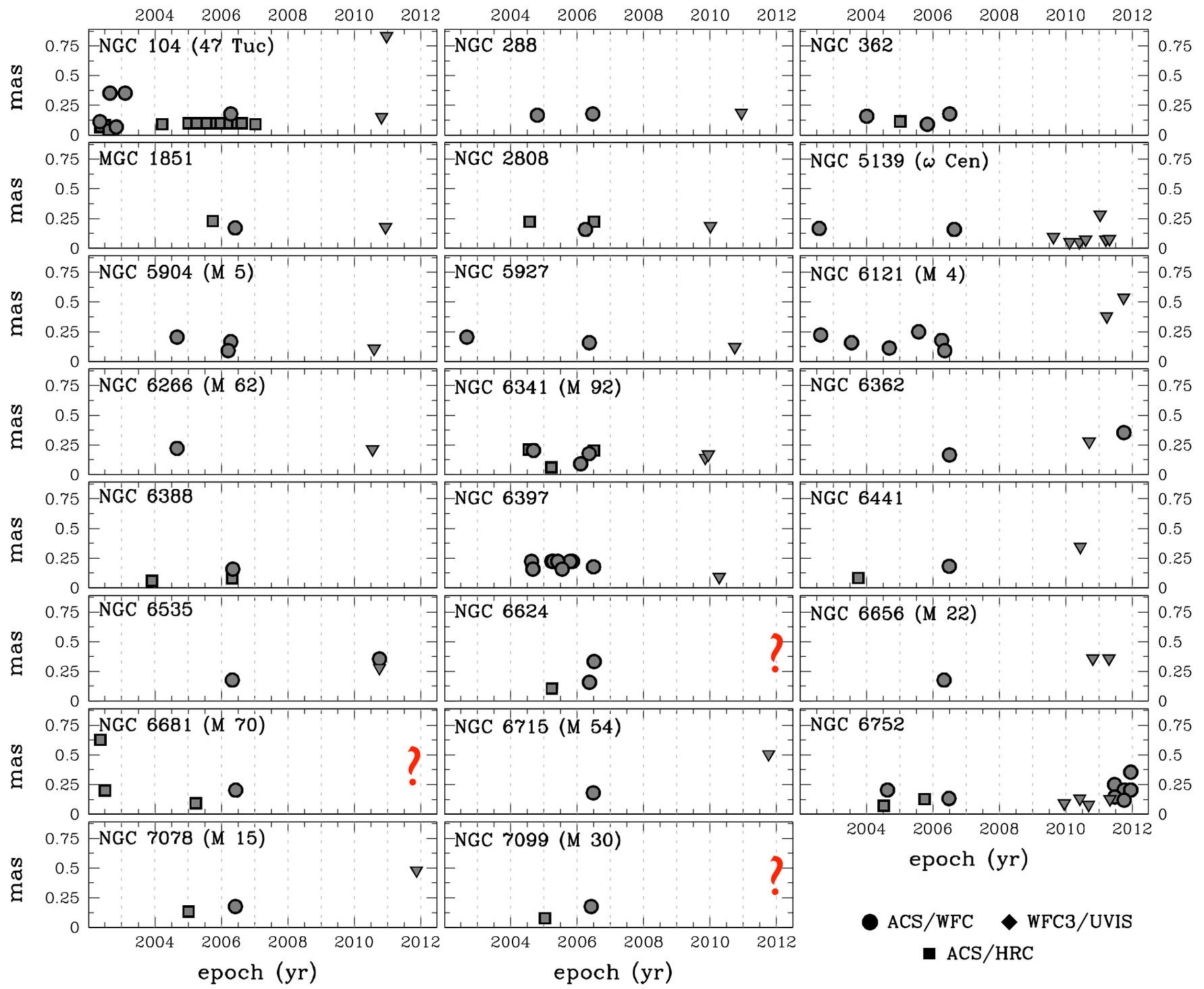

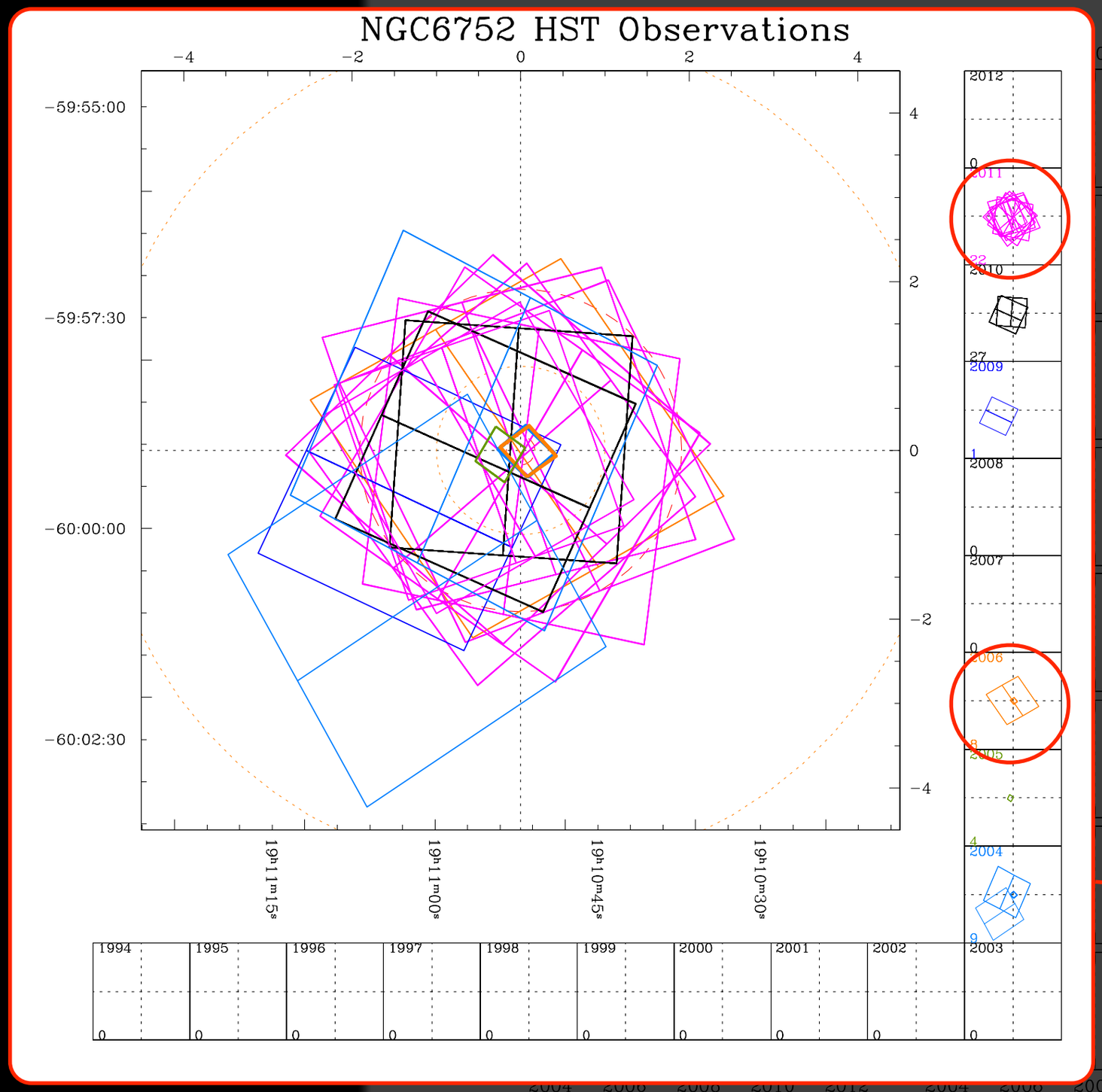
NGC6752 HST Observations
−59:55:00
−59:57:30
−60:00:00
−60:02:30
19h11m15s
19h11m00s
19h10m45s
19h10m30s
1994
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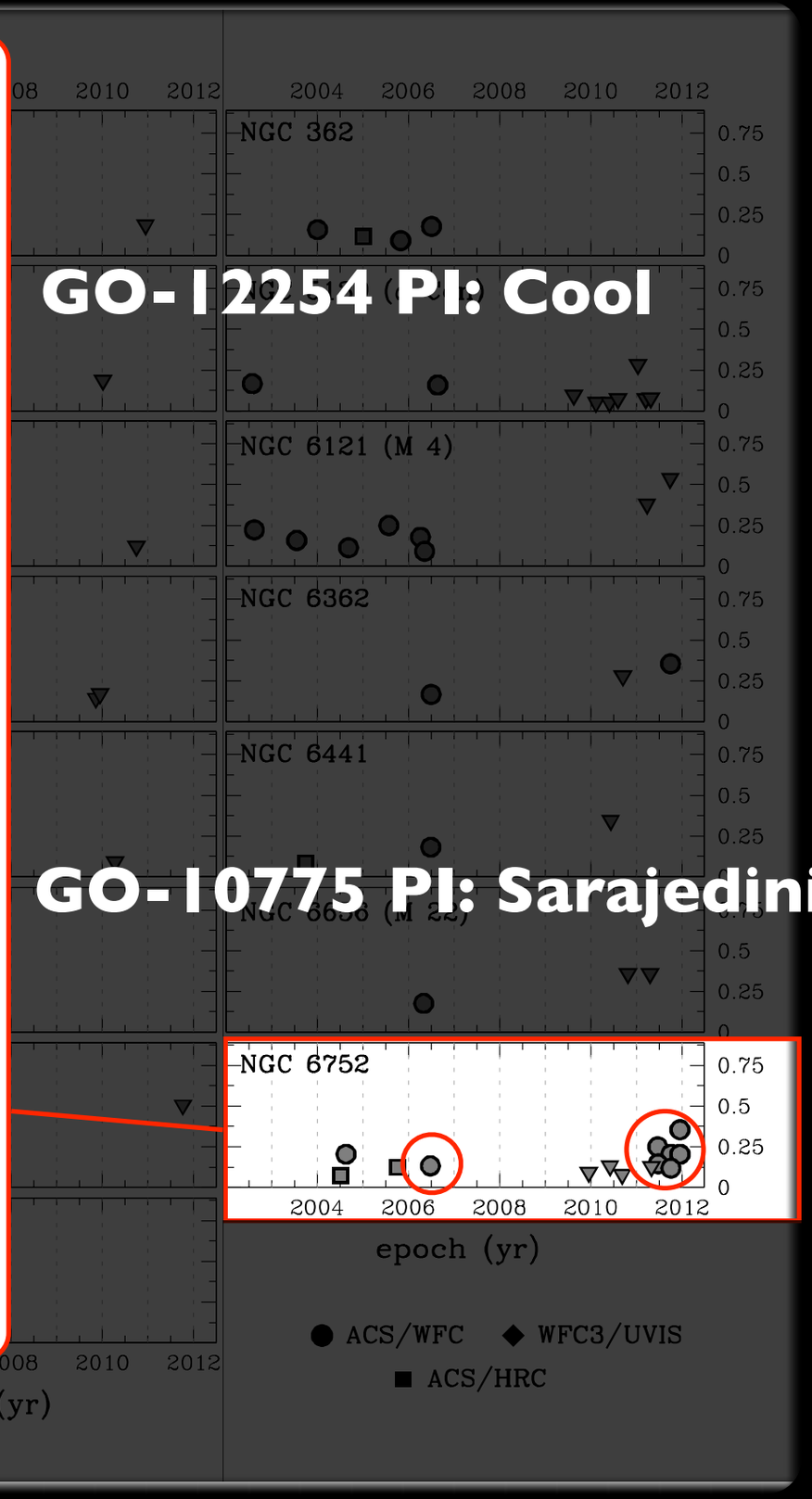
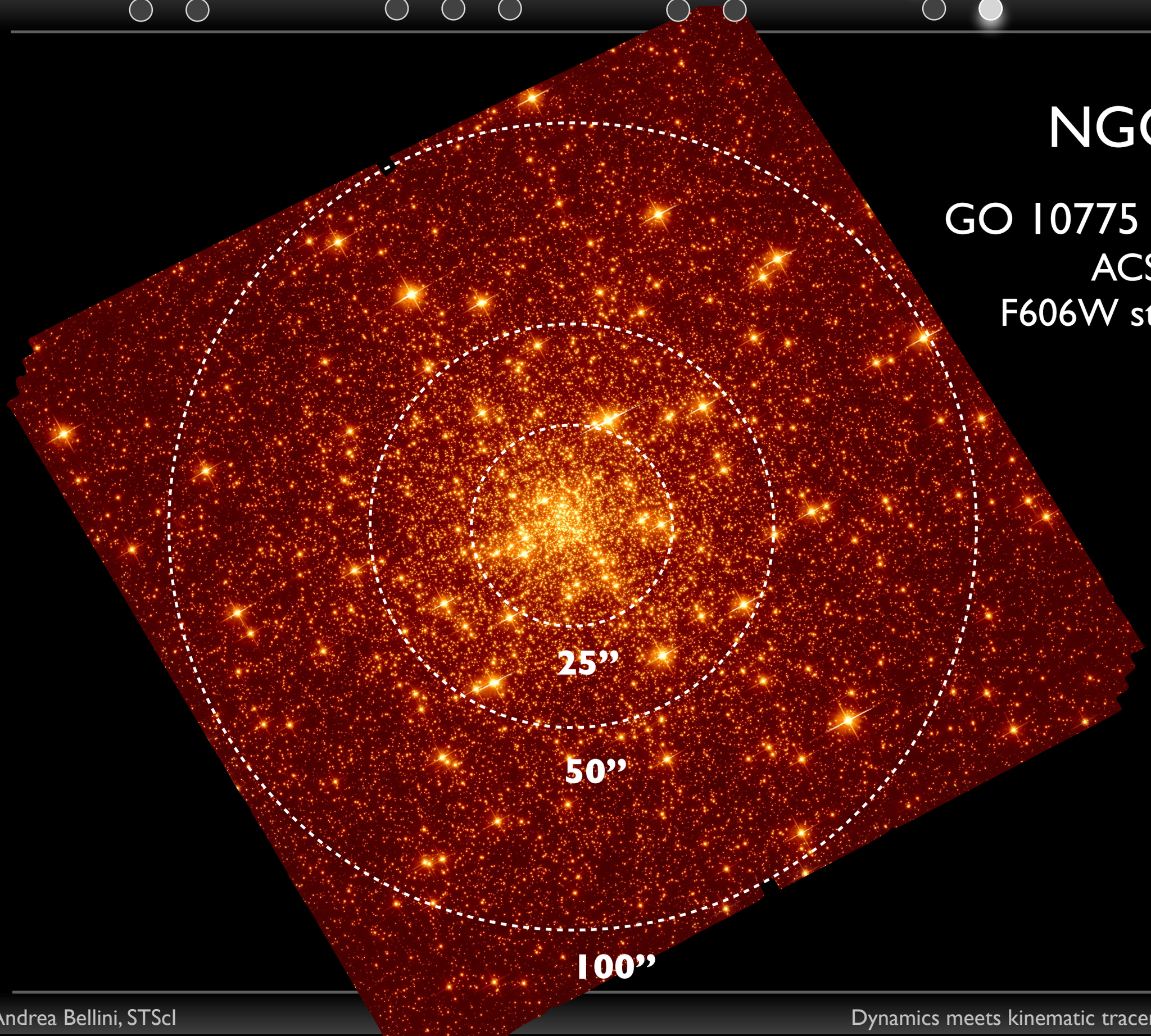
2012

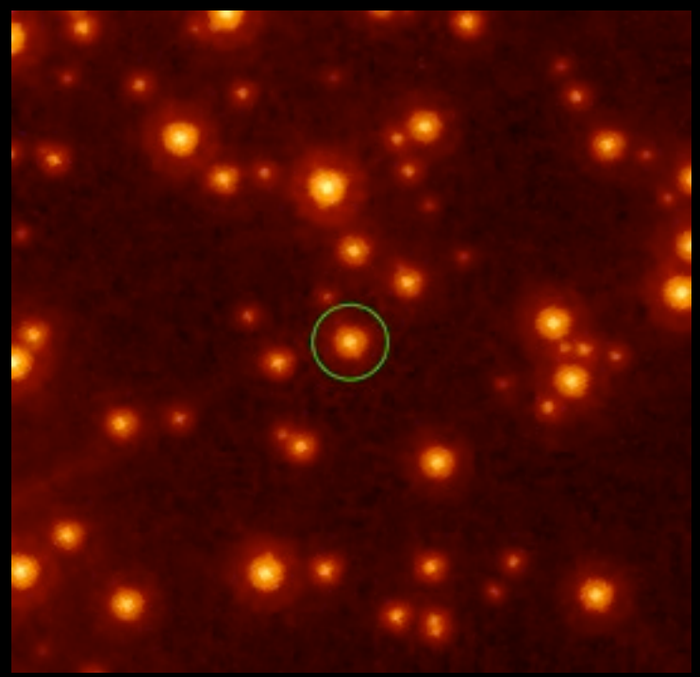
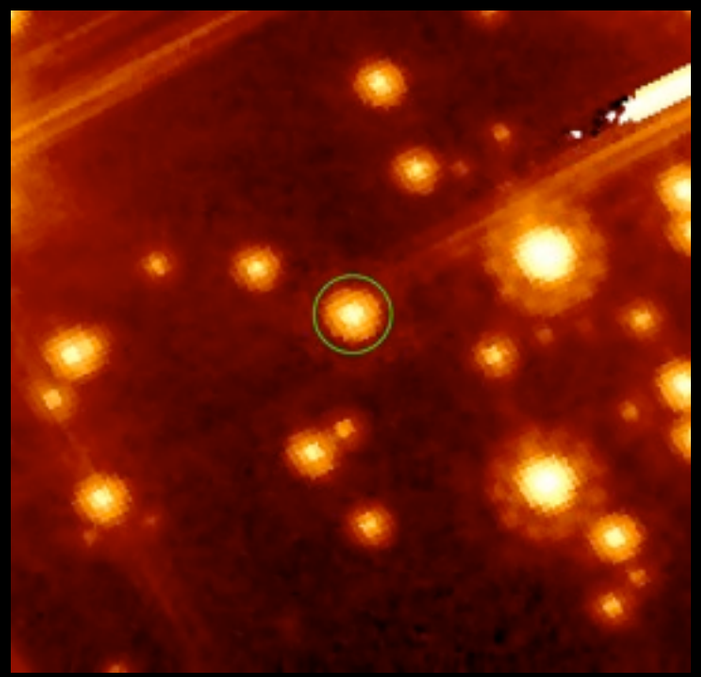
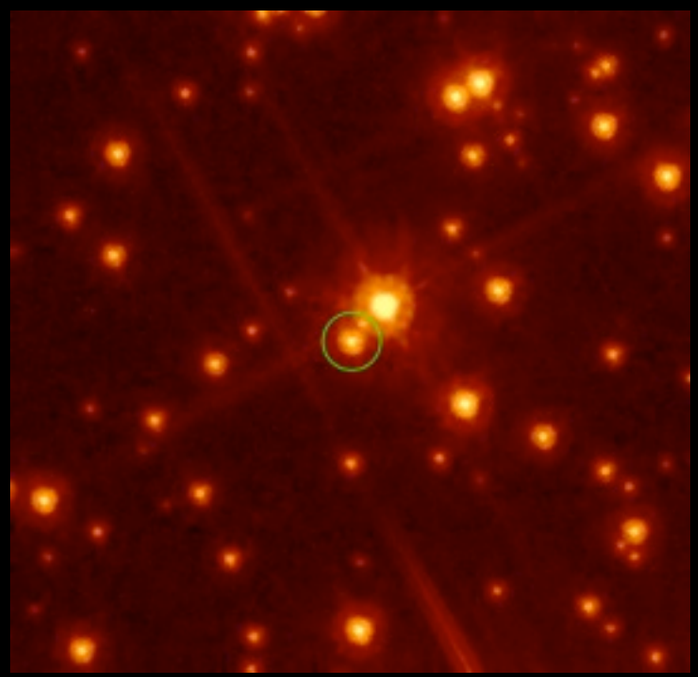

GO-12254 PI: Cool
GO-10775 PI: Sarajedini
NGC 362
NGC 6121 (M 4)
NGC 6362
NGC 6441
NGC 6752
epoch (yr)
ACS/WFC
WFC3/UVIS
ACS/HRC

NGC 6752

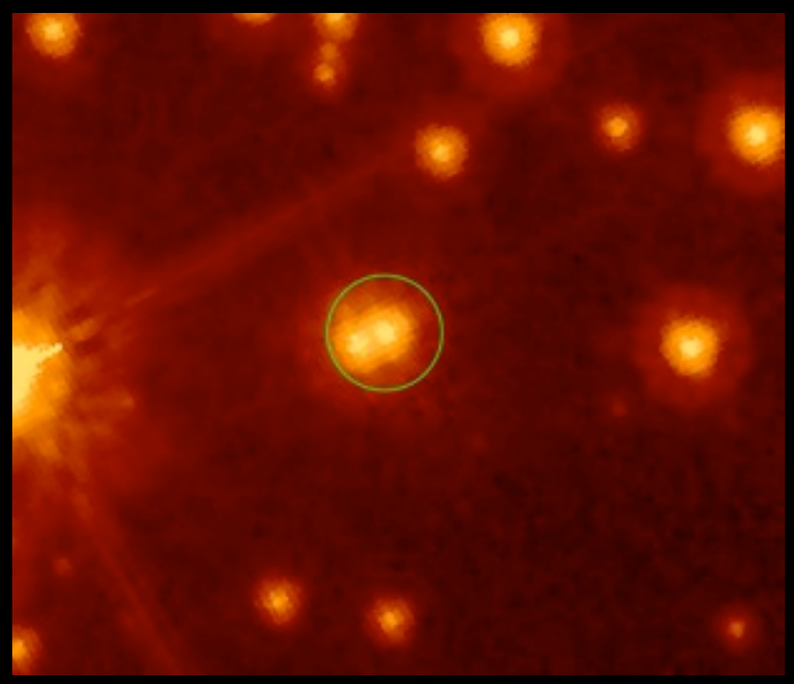
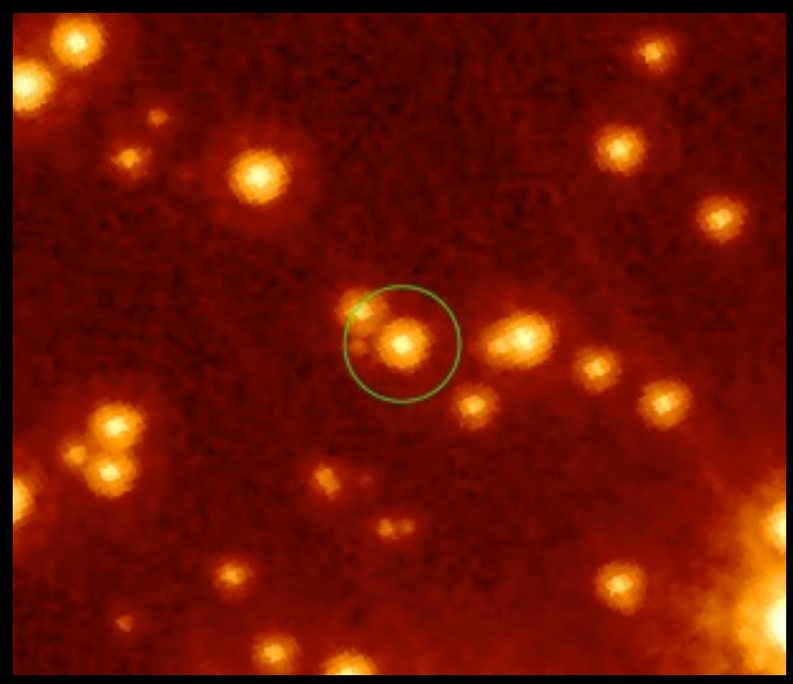
GO 10775 (PI: Sarajedini)
ACS/WFC
F606W stacked image



Proper motion: Cluster and Field stars

blink!

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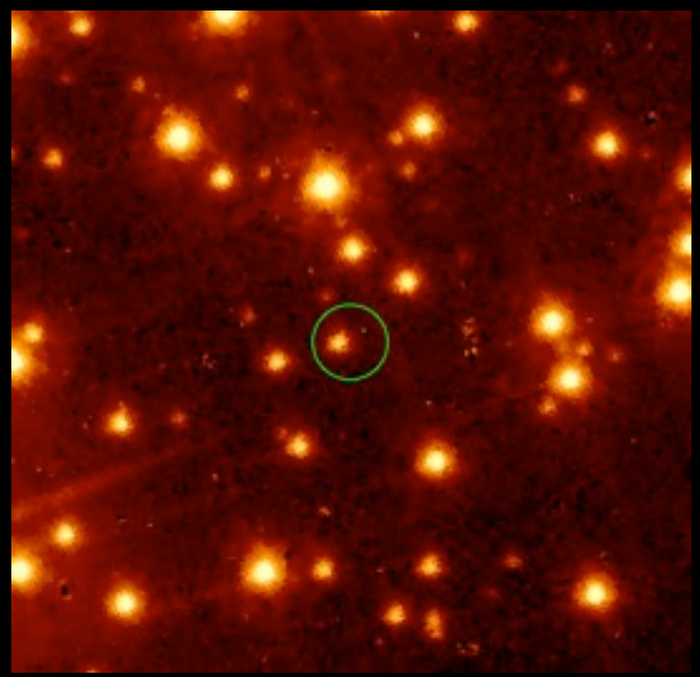
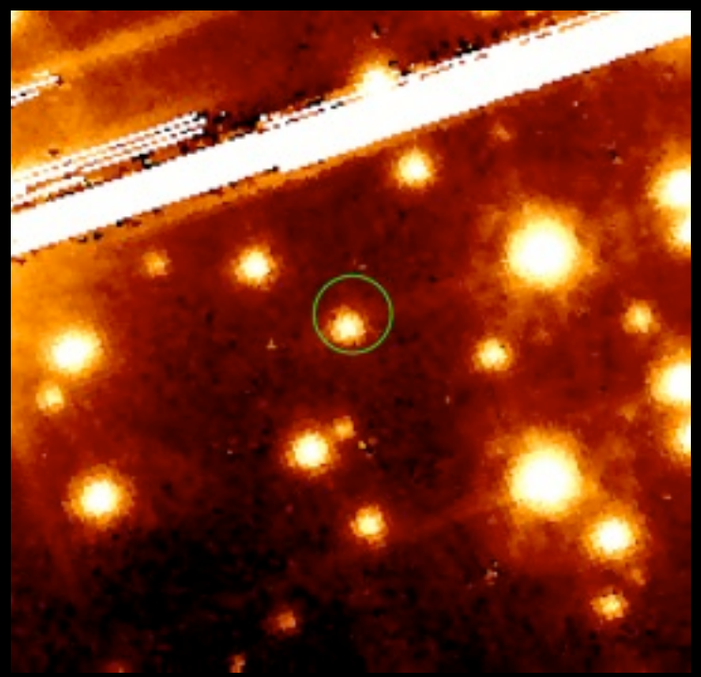
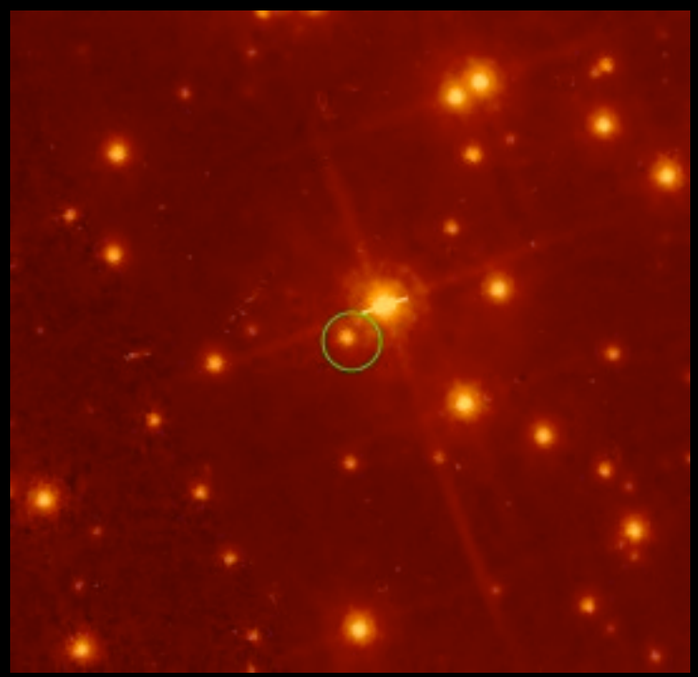
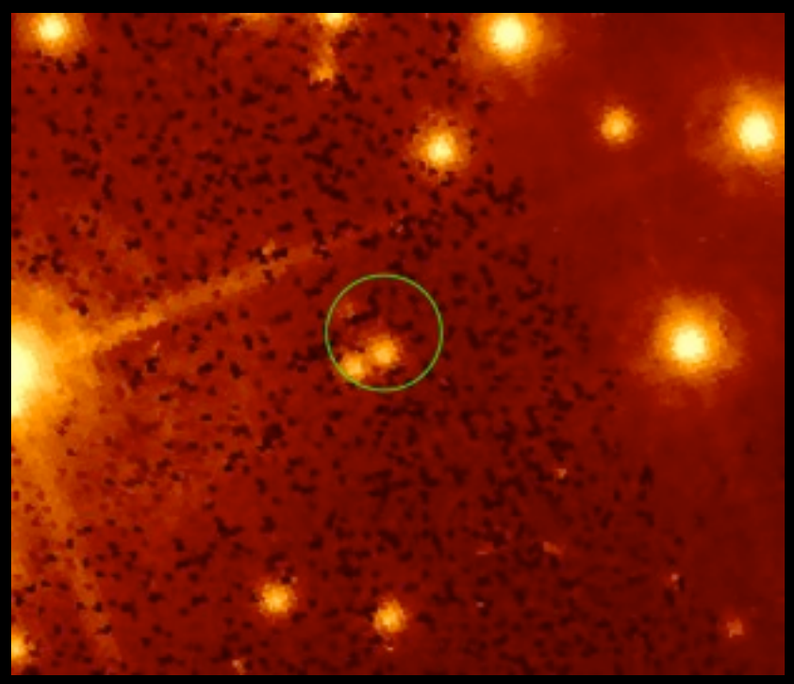
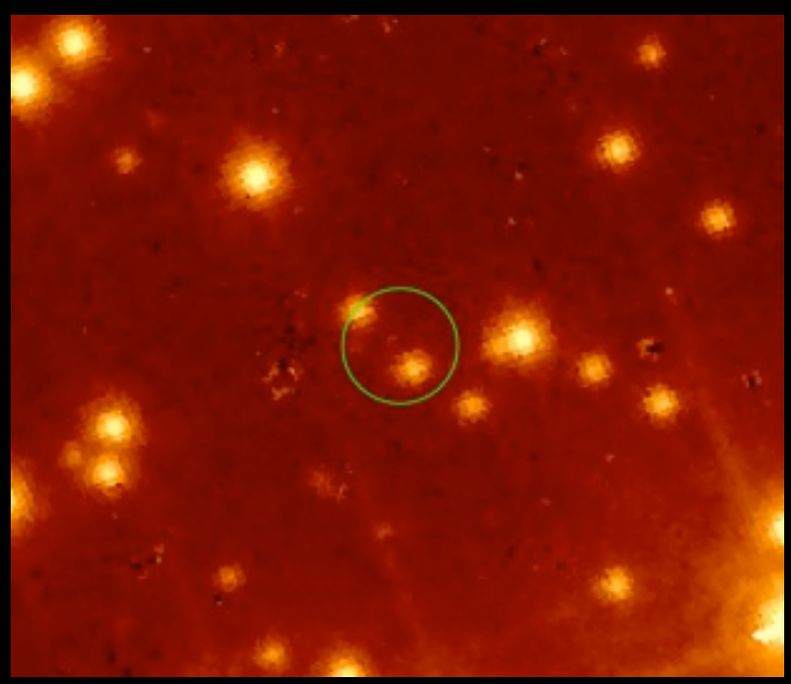
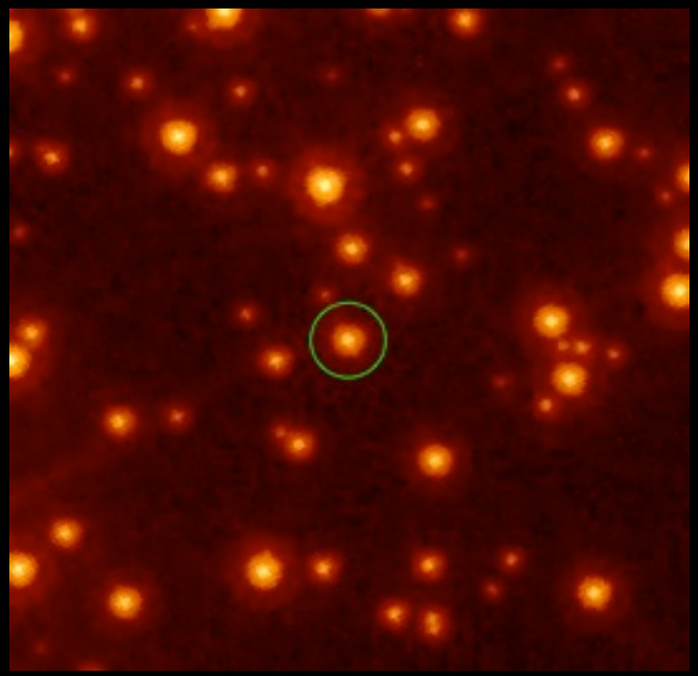
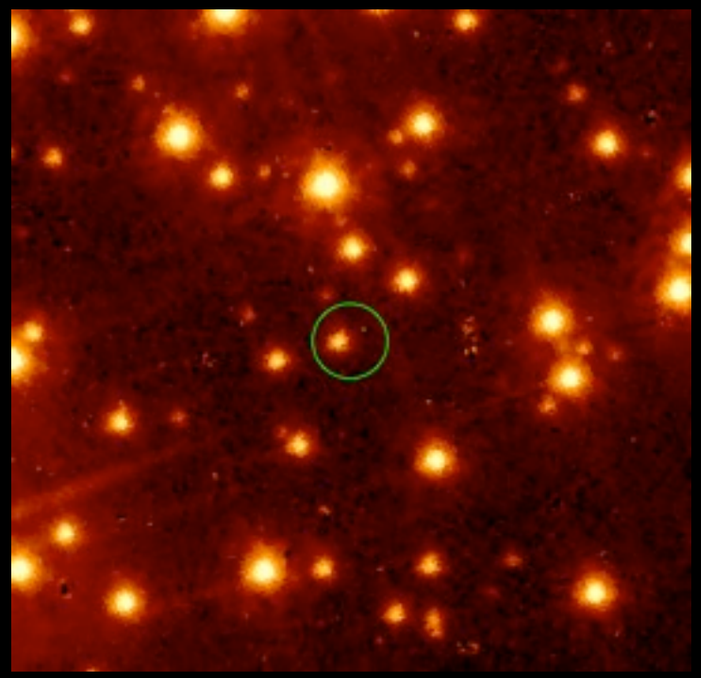
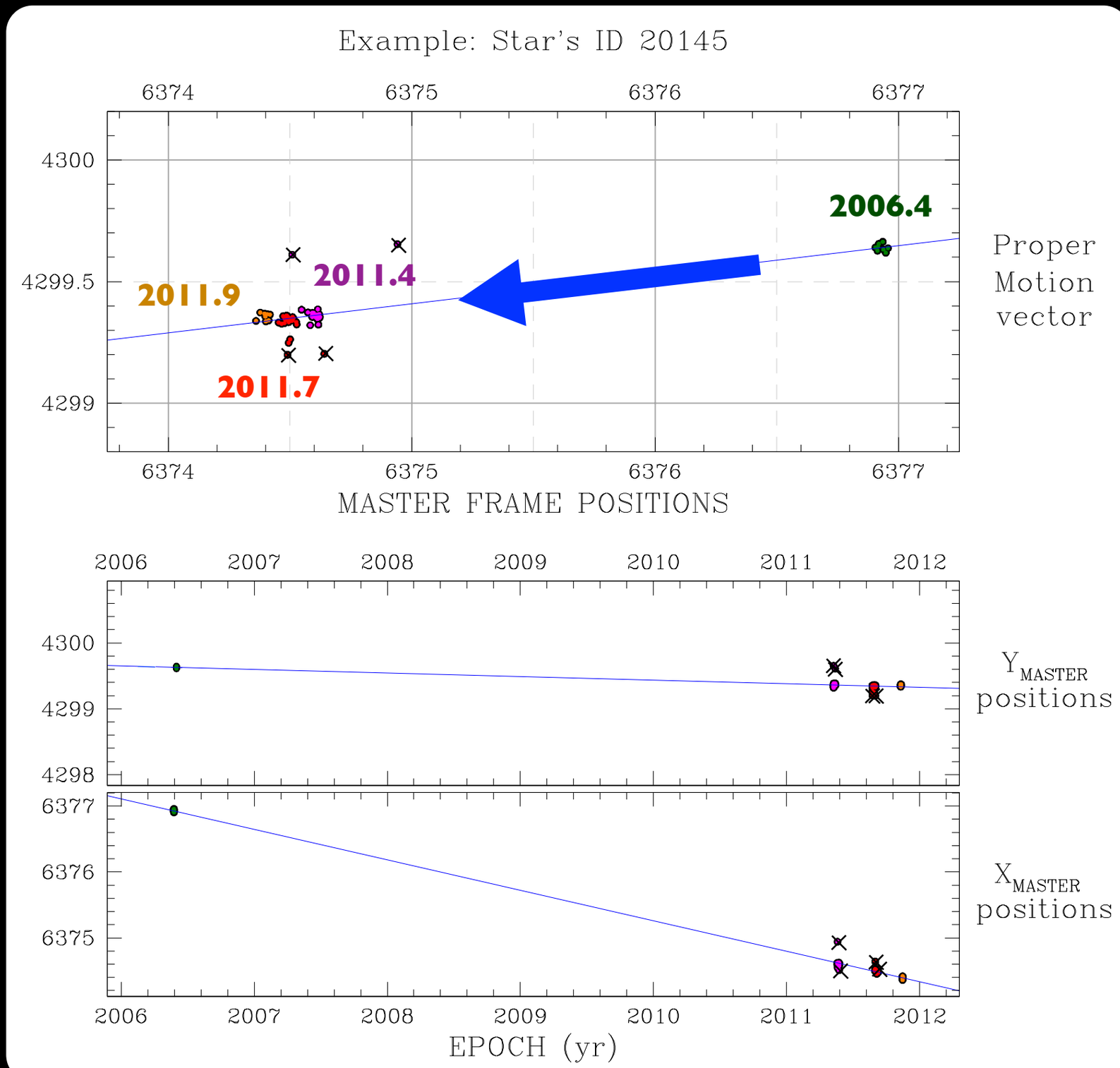






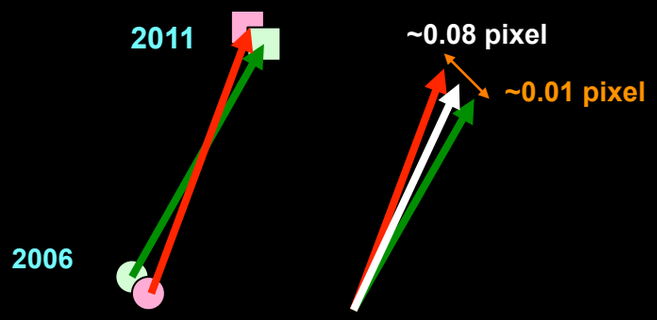
Proper-Motion derivation (GO-10775 & GO-12254)

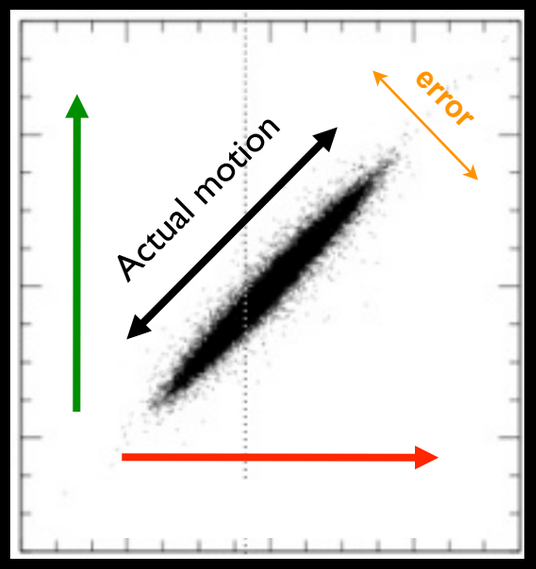


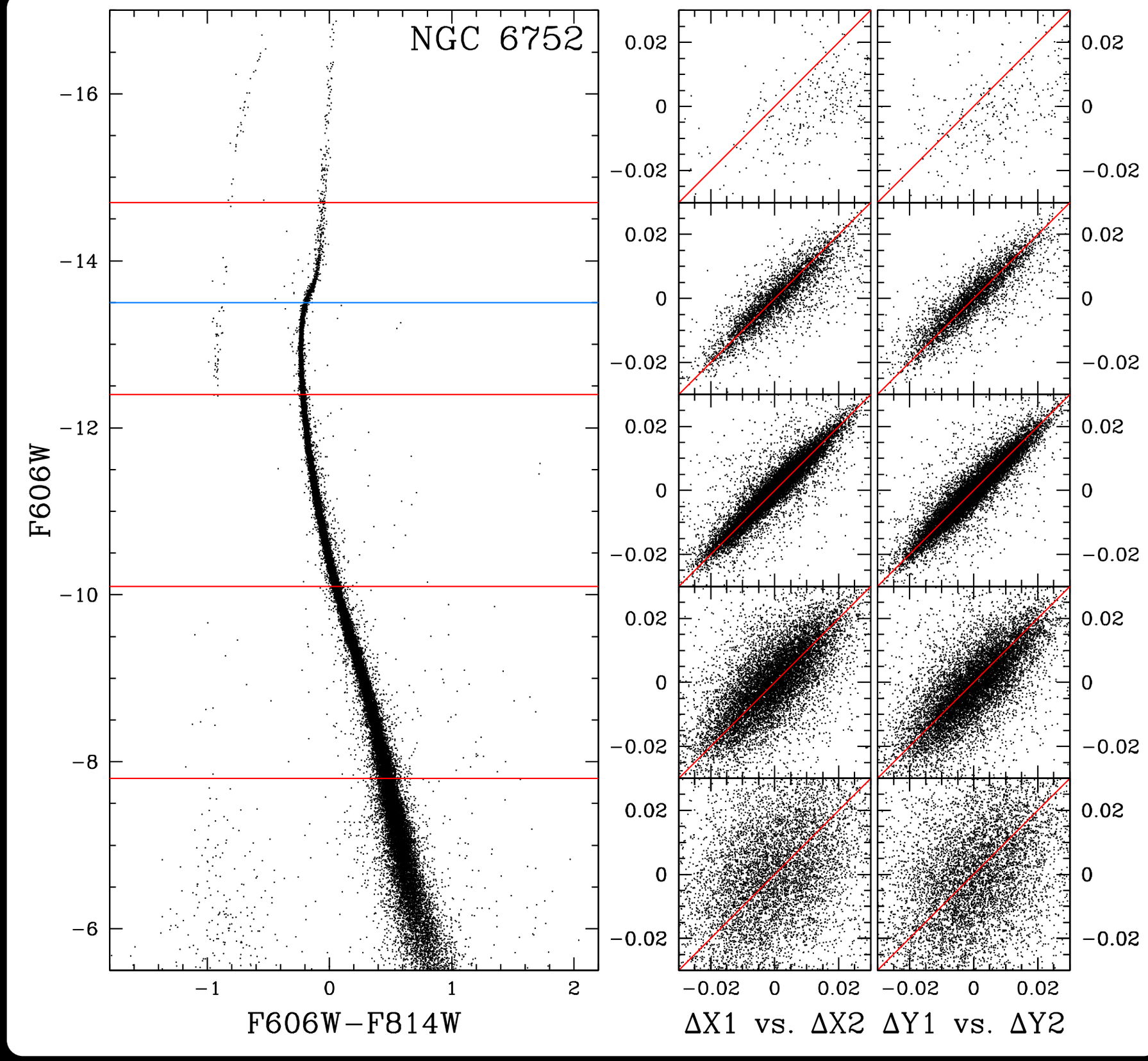


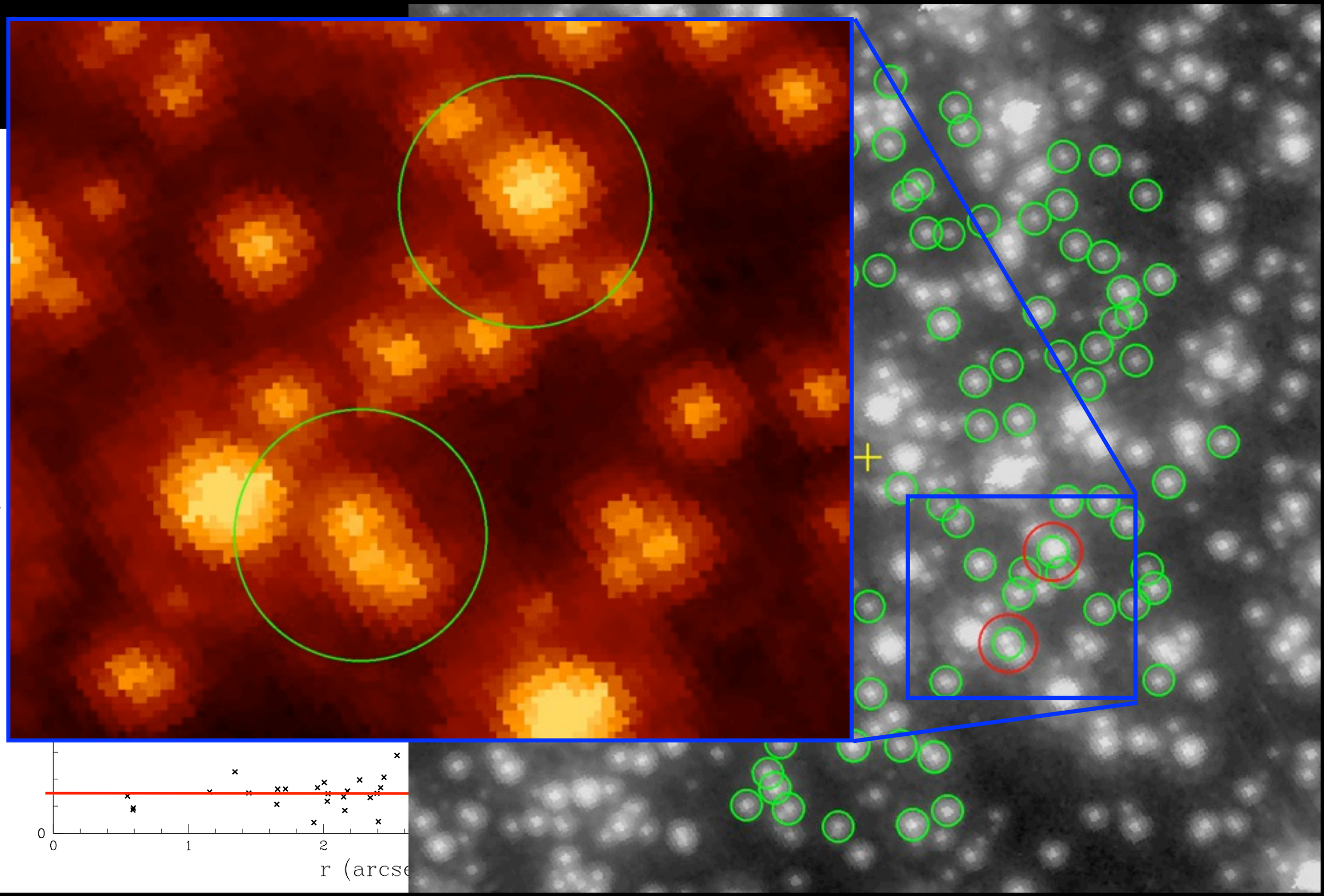


High-quality Internal proper motions for several thousands stars





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Conclusions

High-precision astrometry with *HST* challenging but DOABLE

- undersampling (PSF)
- geometric distortion
- differential nature (local transformations)

Scientific projects with *HST*'s proper motions of GCs

- IMBHs
- dispersion profiles
- anisotropy
- rotation
- ...

Our project

- high-precision (~2km/s per epoch) proper motions in the cores of 23 GCs
- preliminary results encouraging
- panchromatic proper-motion catalogs will be made publicy available