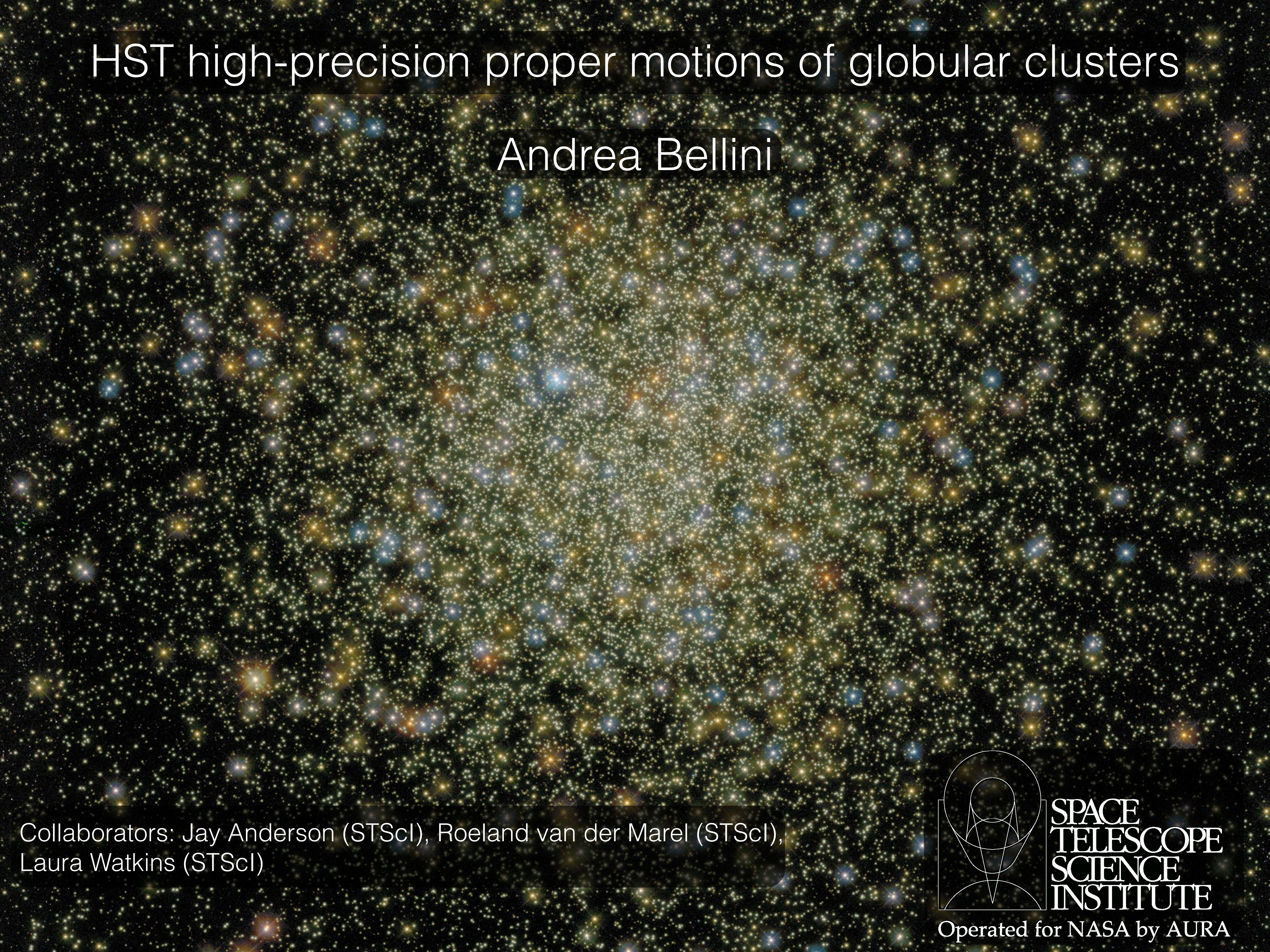


HST high-precision proper motions of globular clusters

Andrea Bellini

Collaborators: Jay Anderson (STScI), Roeland van der Marel (STScI), Laura Watkins (STScI)

SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA

HST high-precision proper motions of globular clusters

Part I: Why we need high-precision HST PMs

- HST vs. Ground
- Science with PMs

Part II: Astrometry with the *HST*

- Undersampling
- CTE / Geometric distortion
- Differential nature

Part III: Our project

- Overview
- PM measuring techniques
- The catalogs

Part IV: Preliminary results

- Internal motion
- Rotation
- Multiple-population kinematics
- Cluster dynamics
- Absolute motion
- Equipartition / (an)isotropy

- **Part I (intro)**
- Part II (techniques)
- Part III (the project)
- Part IV (results)

	HST PMs vs.	GROUND PMs
FOV:	~ 1′	~ 1°
FWHM:	0.1″	1″
Sampling:	undersampled	oversampled
Stars:	V > 17	V < 18
Crowding:	d ~ 0.3″	d ~ 3″
Distortion:	large, but static atmosphere, optics breathing (small)	differential chromatic refraction, seeing, gravity flexure
Reference:	differential	can be absolute
Detector:	better pixels	more pixels
Baseline:	a few years	a few decades
Absolute PMs:	faint, plentiful galaxies	bright, sparse galaxies

…Very different and complementary niches

Scientific applications

1. Cluster-field separation:
   - cluster members
   - Stellar exotica
   - luminosity & mass functions
   - targets for spectroscopic follow-ups
2. Internal motions:
   - detailed kinematics and dynamics
3. Absolute motions
   - Galactic GC orbits
4. Geometric distances
   - distance scale independent from stellar-evolution models and RR Lyrae
5. Clusters rotation
6. Energy equipartition
7. Mass segregation
8. (An)isotropy
9. Full 3D cluster dynamics
   - when LoS velocities for the same stars are available
10. Constraints on IMBHs
    - “shooting stars”
    - sudden increase in the velocity-dispersion profile in the core
11. …

Part I
(intro)

- **Part II (techniques)**

Part III
(the project)

Part IV
(results)

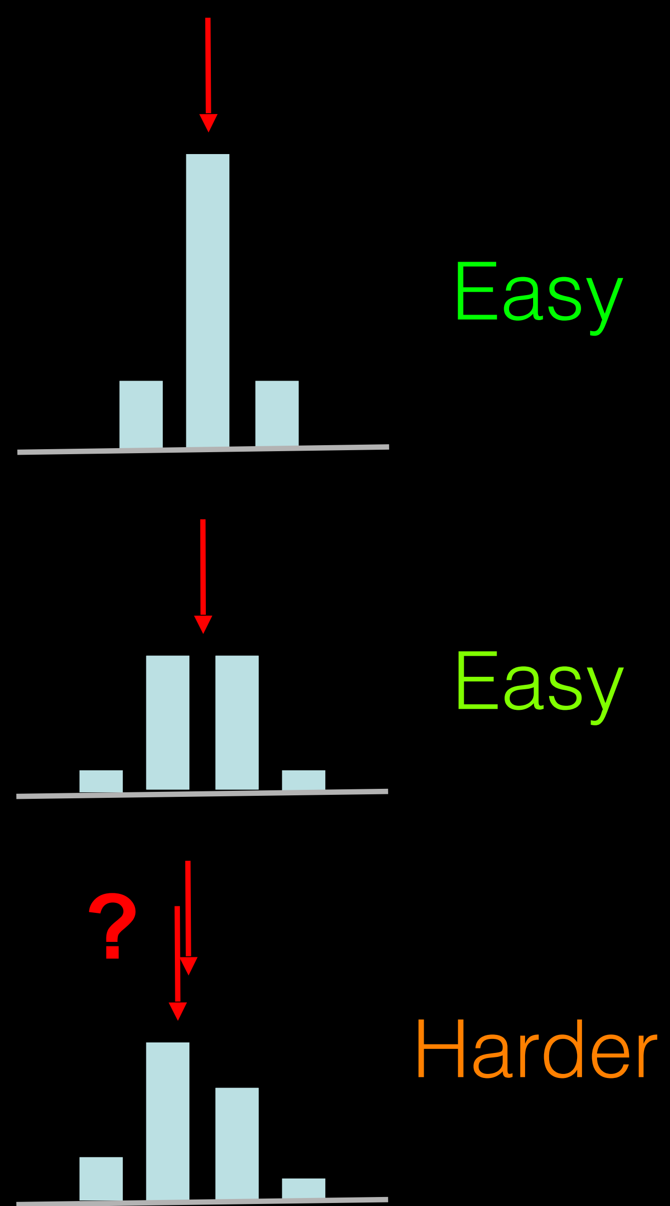
Part II: Astrometry with HST

- undersampling (PSF)
- geometric distortion
- CTE defects
- differential nature

ISSUE#1: Undersampling

Illustration of undersampling conditions

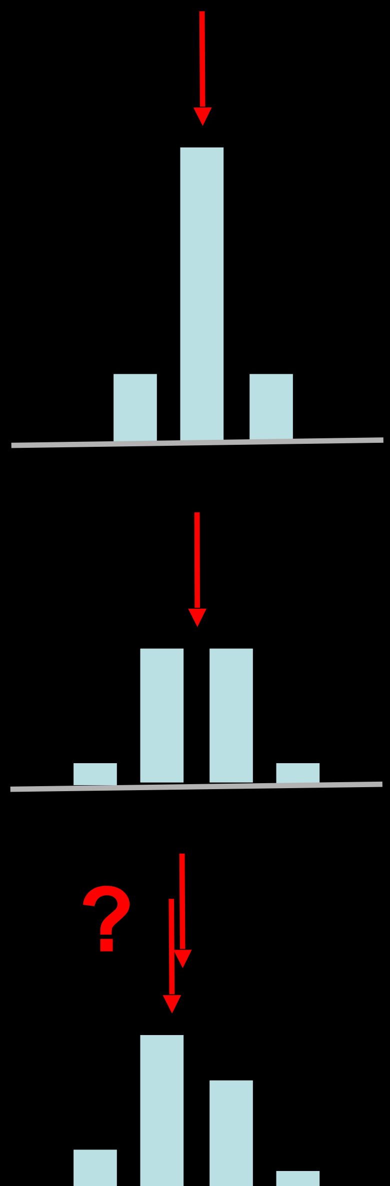
Where is the center?



ISSUE#1: Undersampling

Illustration of undersampling conditions

Where is the center?

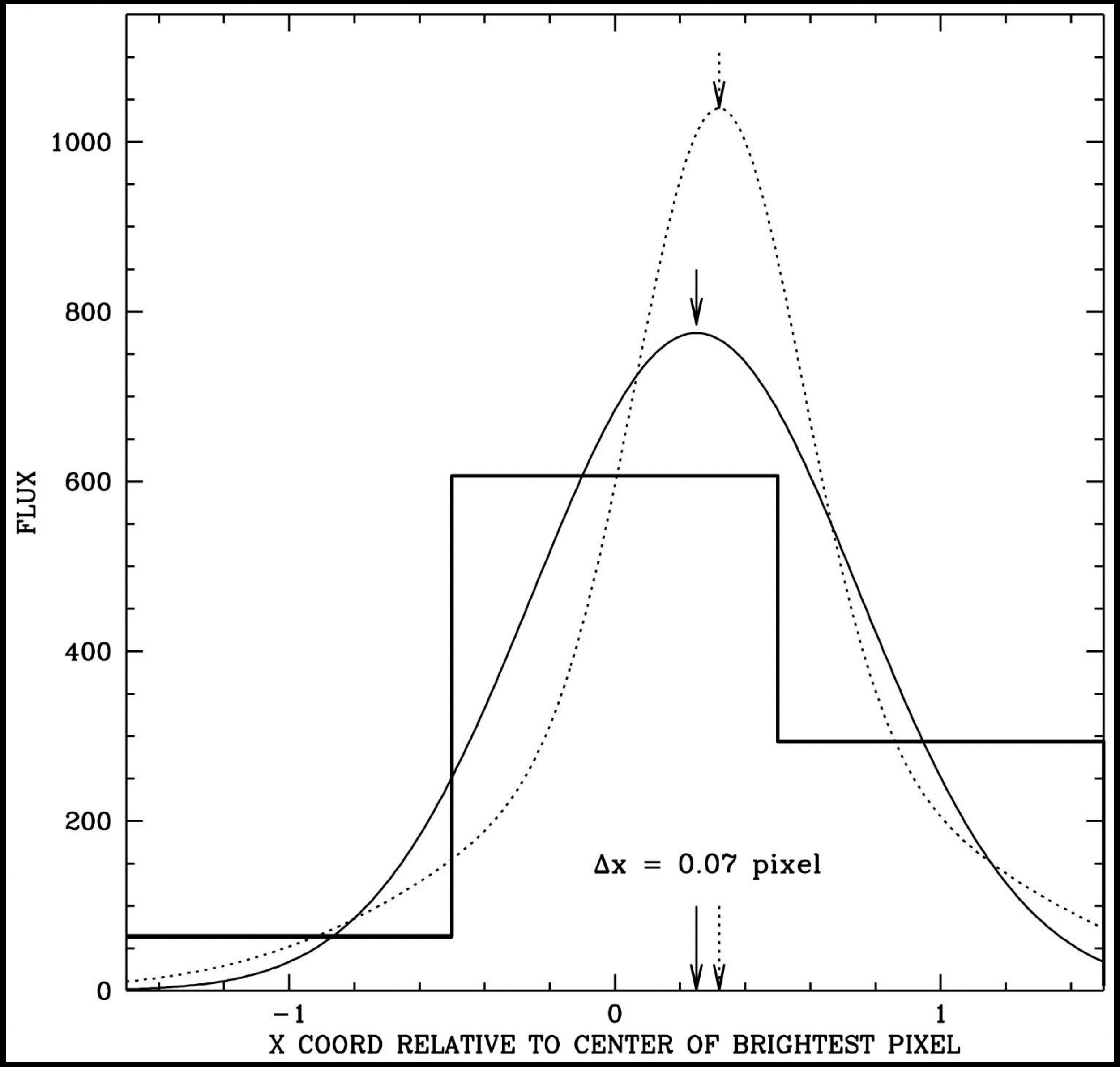


Easy

Easy

Harder

Anderson & King 2000, PASP 112, 1360



Part I (intro)
· **Part II (techniques)**
Part III (the project)
Part IV (results)

ISSUE#1: Undersampling and Astrometry

Impossible?

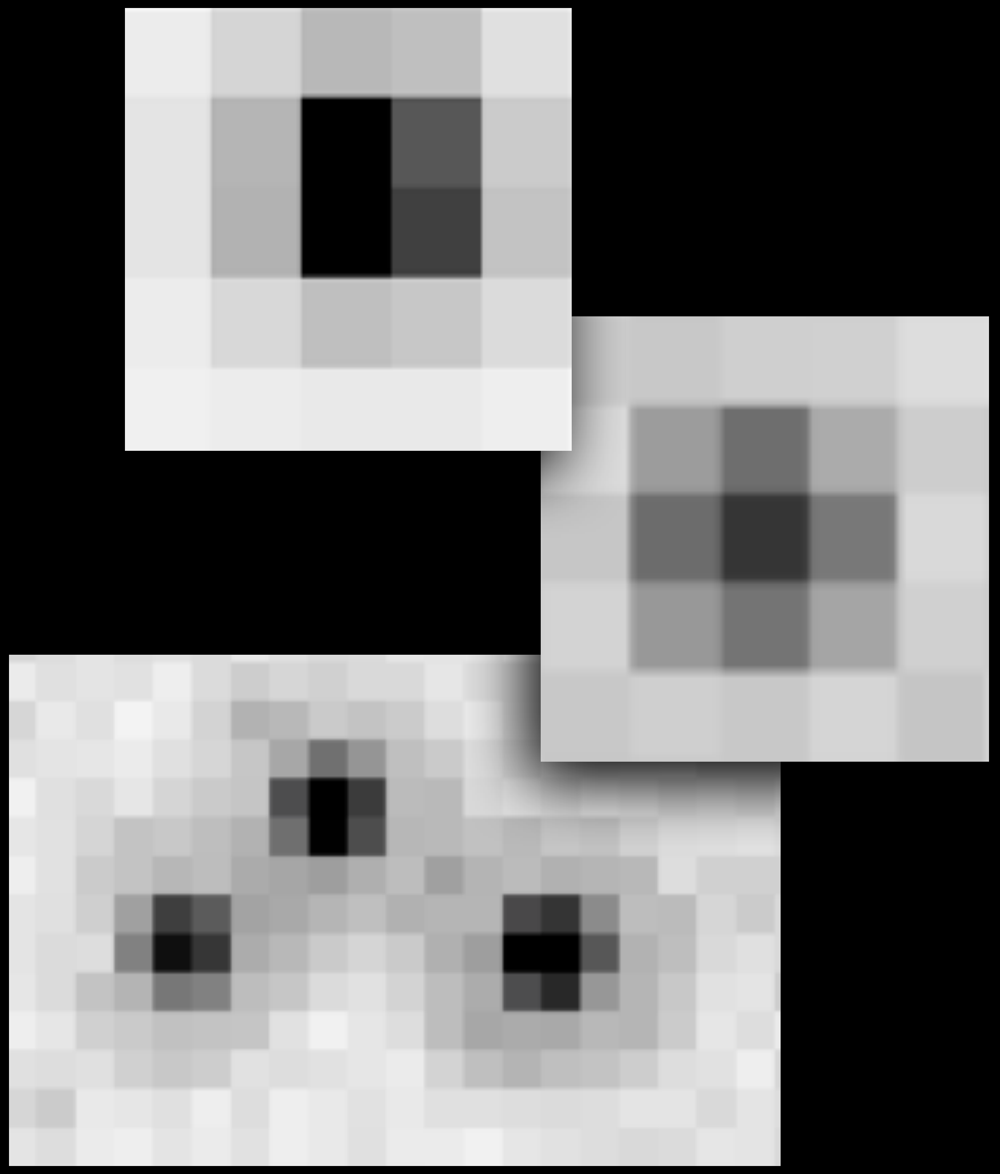
– A point source has “no hair”
  - 3 parameters (x_*,y_*,f), ~9 pixels
– Minimal requirements: “slosh”

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



Part I
(intro)

- **Part II (techniques)**

Part III
(the project)

Part IV
(results)

ISSUE#1: what do we mean by the PSF?

$\psi_{INST}(\Delta x,\Delta y)$: the “Instrumental” PSF:

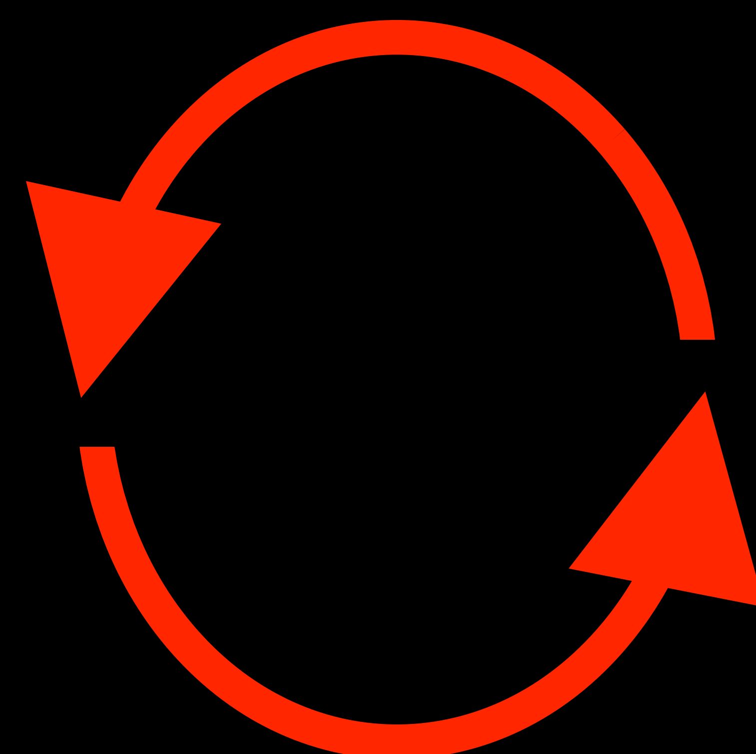
- The PSF as it hits the detector
- Good theoretical motivations: Gaussians, Moffat
- See ψ_{INST} only indirectly in images
- To solve for: must deconvolve the PSF from the pixels

$\psi_{EFF}(\Delta x,\Delta y)$: the “Effective” PSF:

- The PSF after pixelization: $\psi_{EFF} = \psi_{INST} \otimes \Pi$
- Empirical: no natural basis function to describe
- We never deal with anything BUT the effective PSF
  - See ψ_{EFF} directly in images
  - Can measure ψ_{EFF} directly from images

ISSUE#1: Finding vs. Using the ePSF

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



- Iteration
  - Dithers break the degeneracy!

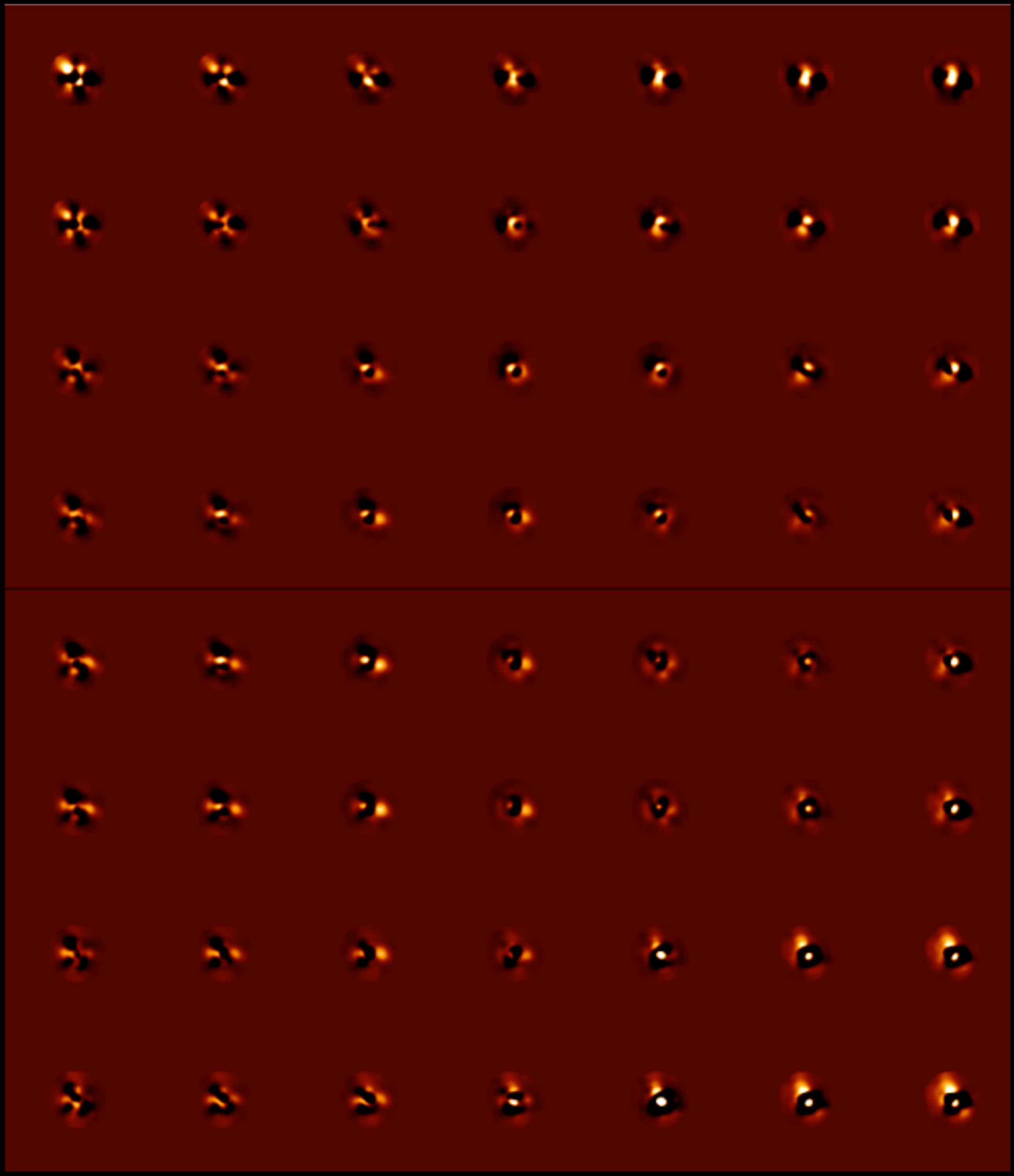
ISSUE#1: High-level PSF issues

- Spatial variability:

- Core intensity varies up to ±10% over scales of ~500 pixels.

- Time variability (breathing)

- Core intensity varies up to ±10% from one exposure to the next



Part I
(intro)

· **Part II
(techniques)**

Part III
(the project)

Part IV
(results)

ISSUE#2: Geometric distortion

Why? Fewer reflections, better throughput

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

Need empirical approach: plot everything against everything else…

Part I
(intro)

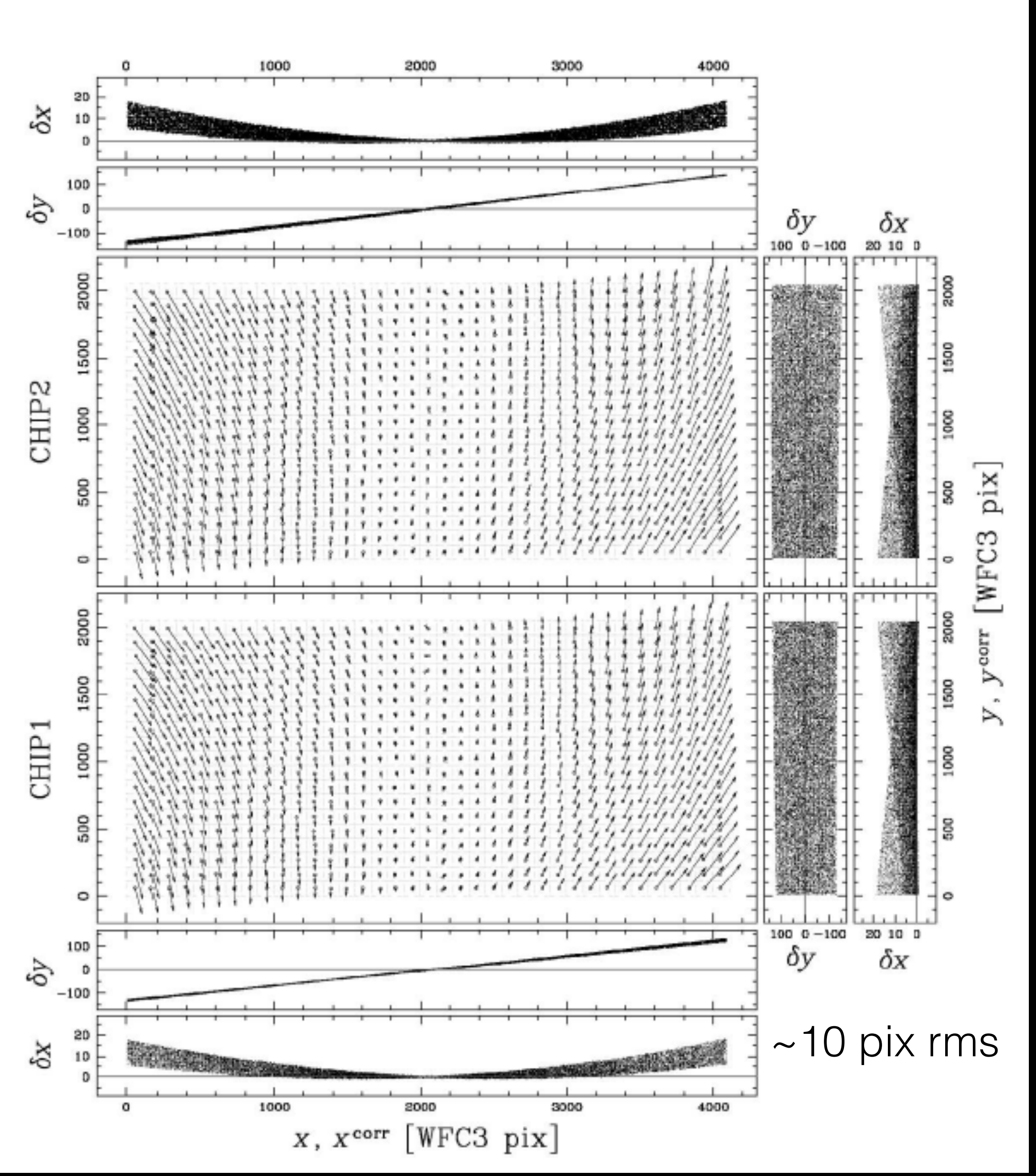
- **Part II (techniques)**

Part III
(the project)

Part IV
(results)

ISSUE#2: Geometric distortion

WFC3/UVIS observed distortion



~10 pix rms

Bellini & Bedin 2009, PASP, 121, 1419

Part I (intro)

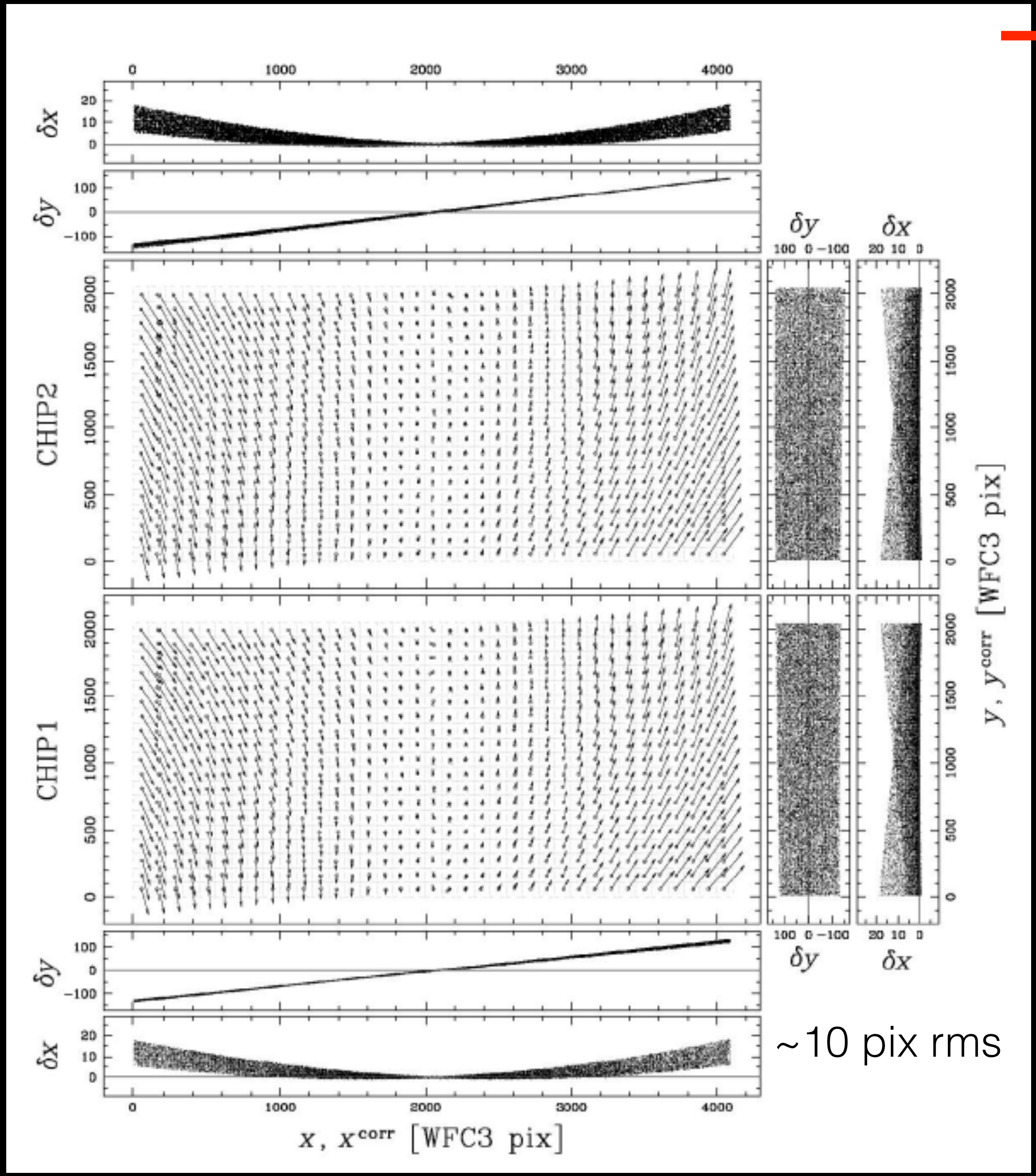
· **Part II (techniques)**

Part III (the project)

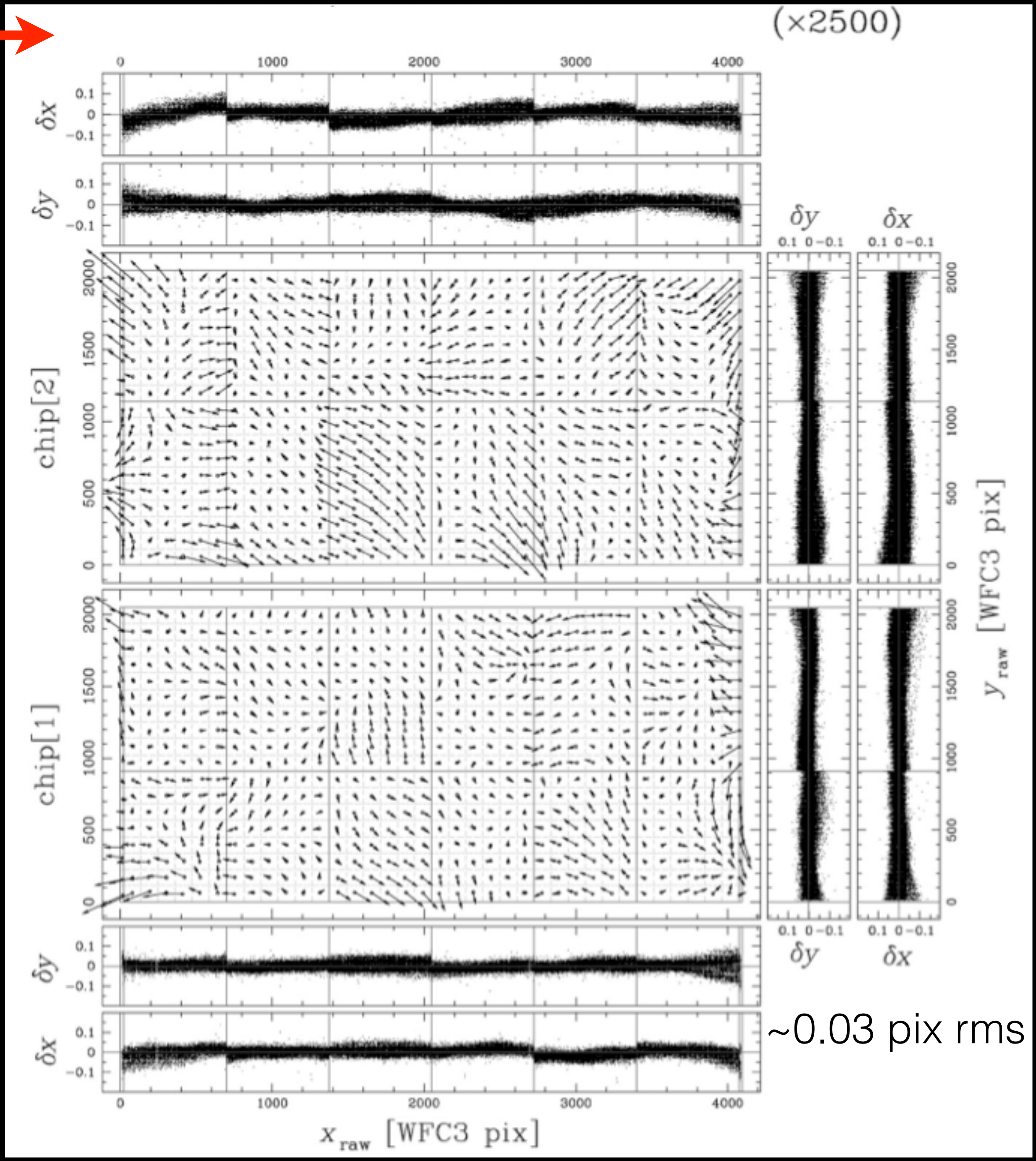
Part IV (results)

ISSUE#2: Geometric distortion

auto-calibration & polynomial solution



~10 pix rms



~0.03 pix rms

Bellini & Bedin 2009, PASP, 121, 1419

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

Part I
(intro)

· **Part II
(techniques)**

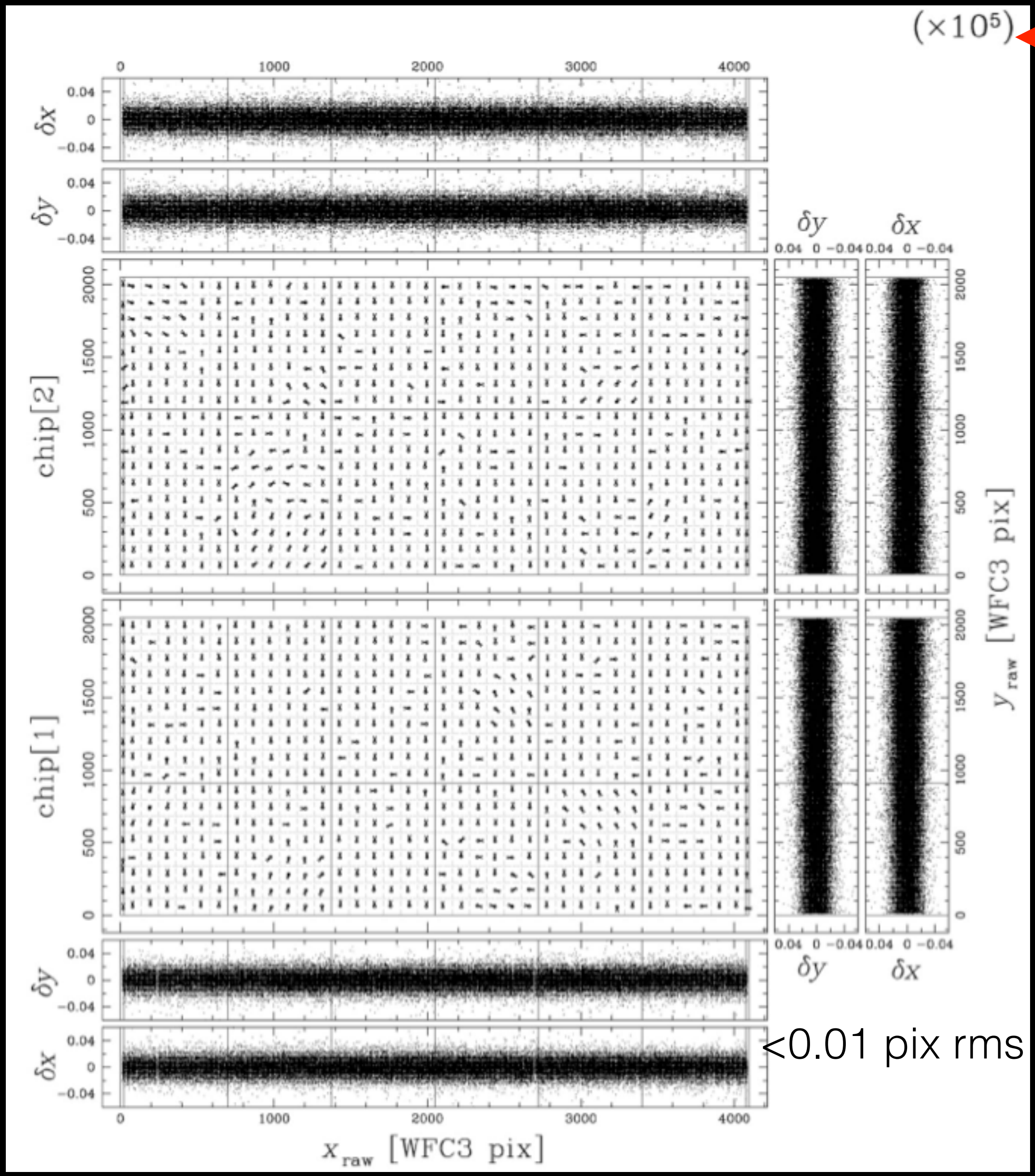
Part III
(the project)

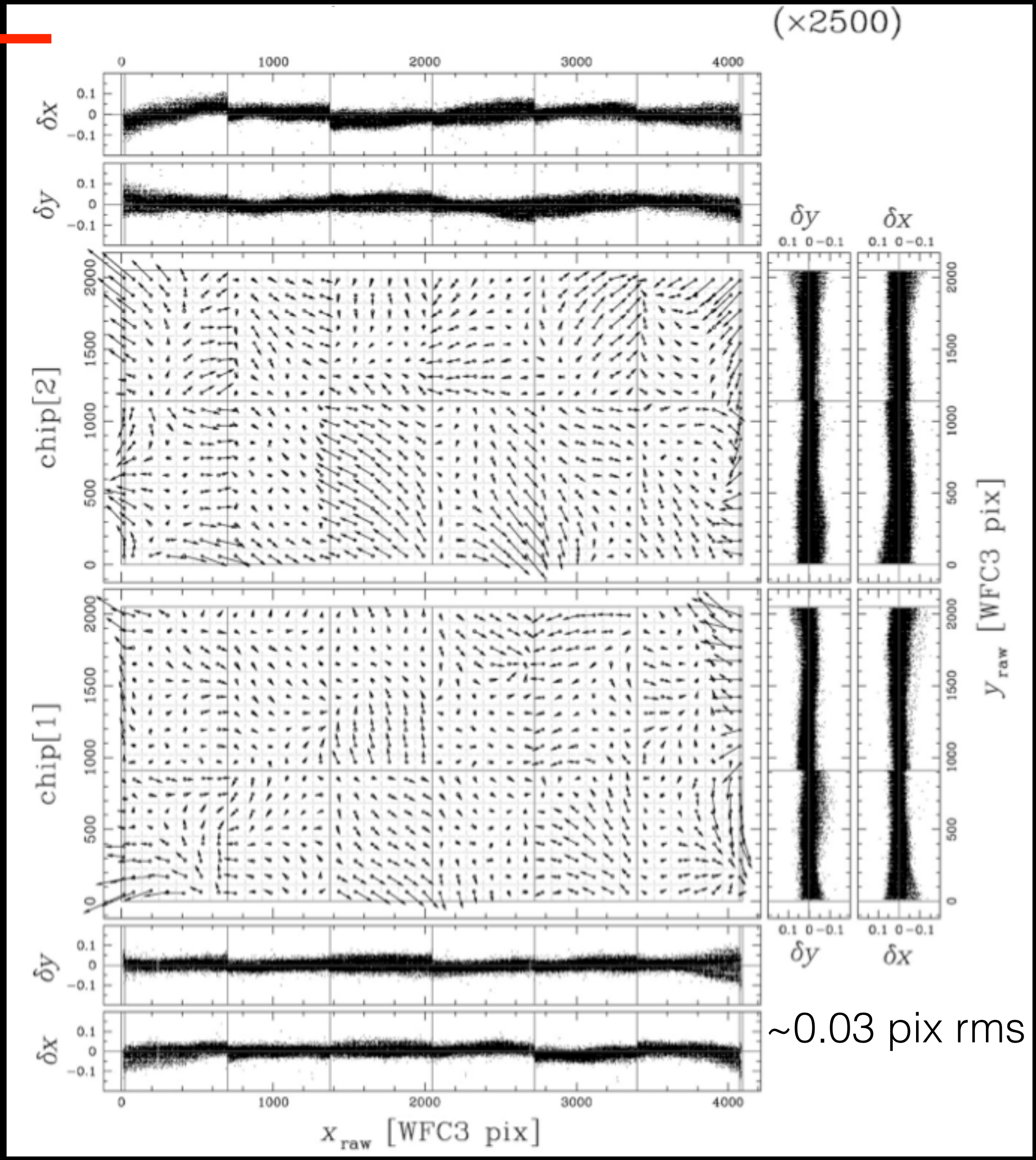
Part IV
(results)

ISSUE#2: Geometric distortion

Table-of-residuals correction

Astrometric flat-field to the < 0.01-pixel level





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

Part I
(intro)

· **Part II
(techniques)**

Part III
(the project)

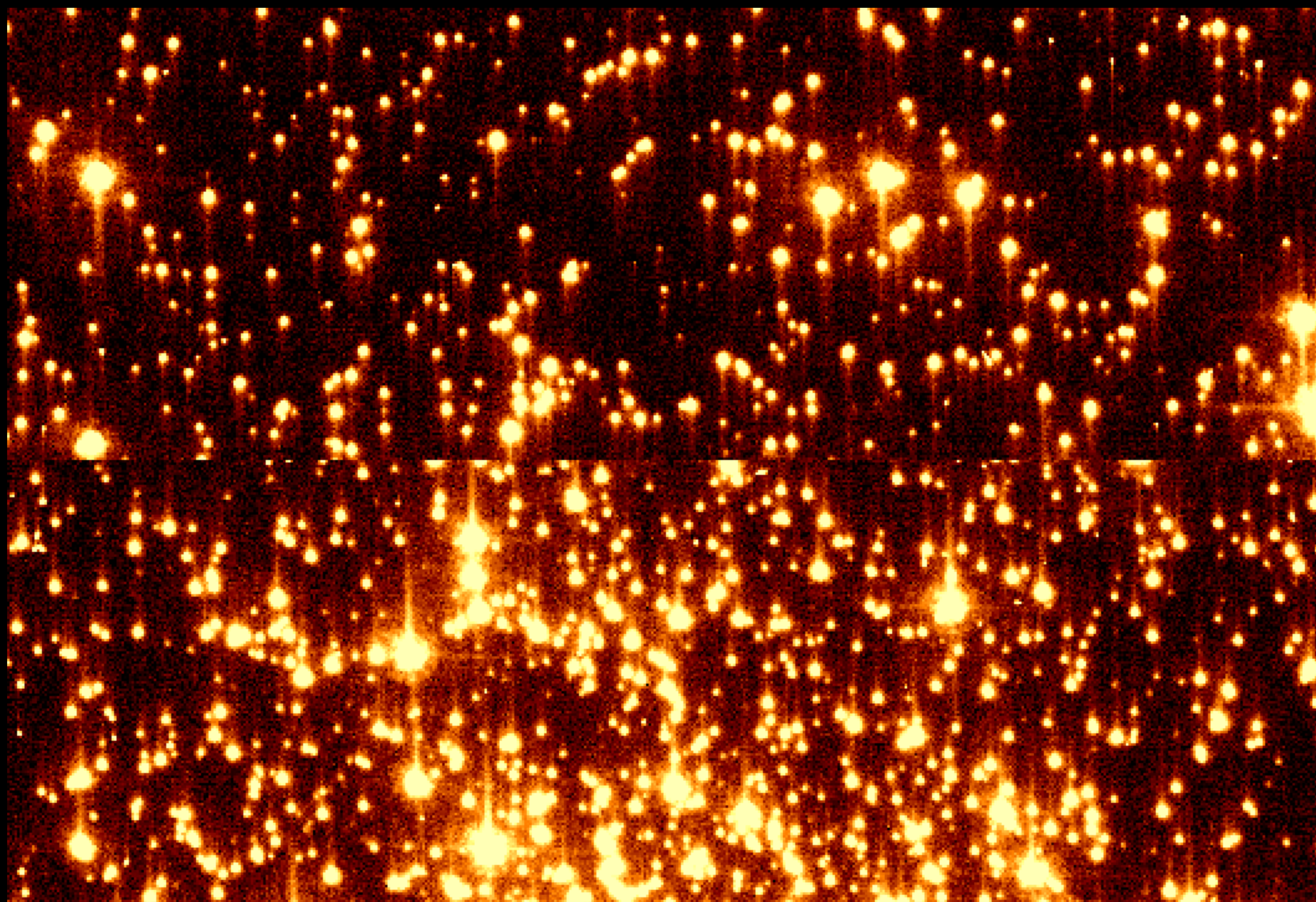
Part IV
(results)

ISSUE#3: CTE defects

Affect ALL CCD detectors (ground- and space-based)

Increase with time

Are a function of stellar brightness, chip position, and background level



Part I
(intro)

· **Part II (techniques)**

Part III
(the project)

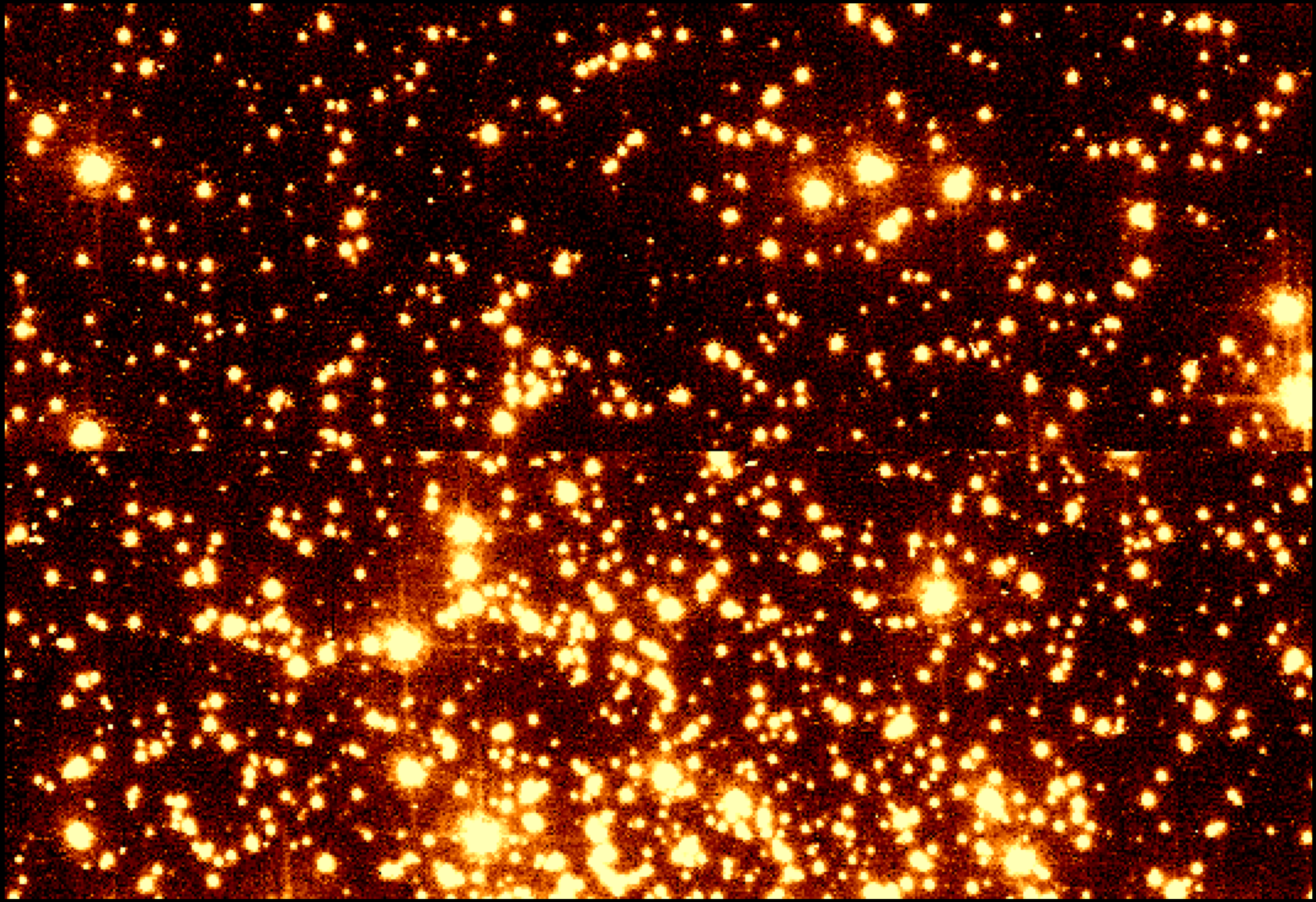
Part IV
(results)

ISSUE#3: CTE defects

Affect ALL CCD detectors (ground- and space-based)

Increase with time

Are a function of stellar brightness, chip position, and background level



Anderson & Bedin (2010)

Part I
(intro)

· **Part II**
(techniques)

Part III
(the project)

Part IV
(results)

ISSUE#4: Transformations

All HST astrometry is differential astrometry

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

Always need to define a local reference frame

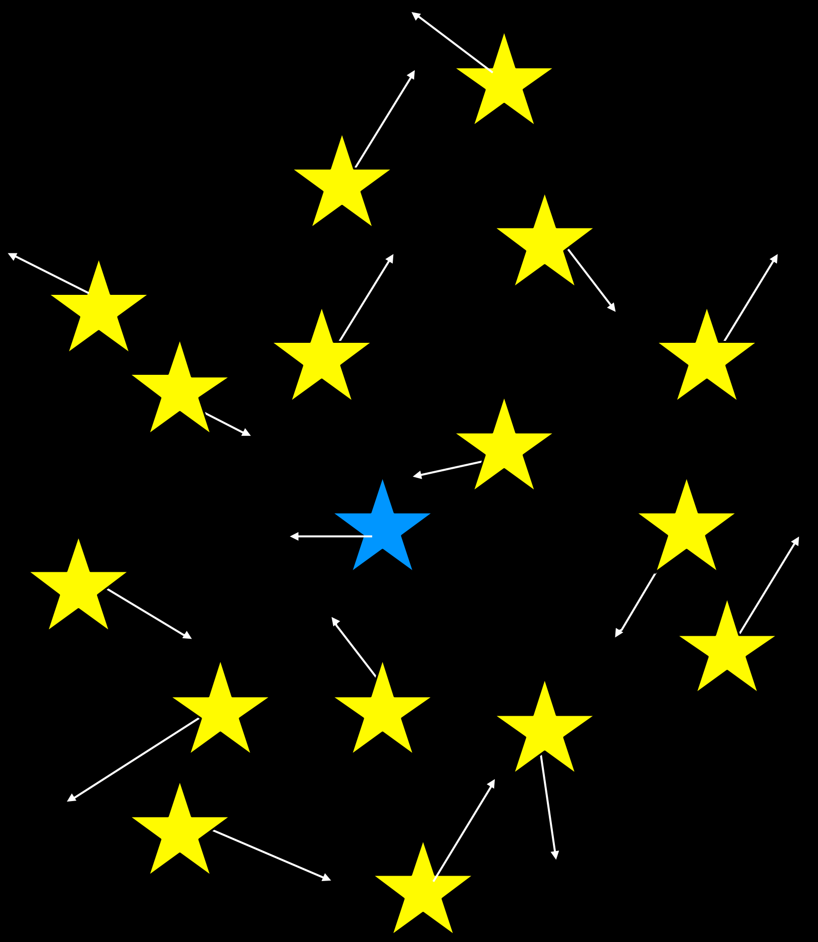
- Pixels/positions have only relative meaning
- Choosing a frame
  - Base it on a population of objects (3+) in the frame
  - Must know a priori something about the population
    - → absolute $\mu = 0$ (galaxies)
    - → average μ = same (clusters)
    - → average μ = unchanging (field)

Part I (intro)
· **Part II (techniques)**
Part III (the project)
Part IV (results)

ISSUE#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

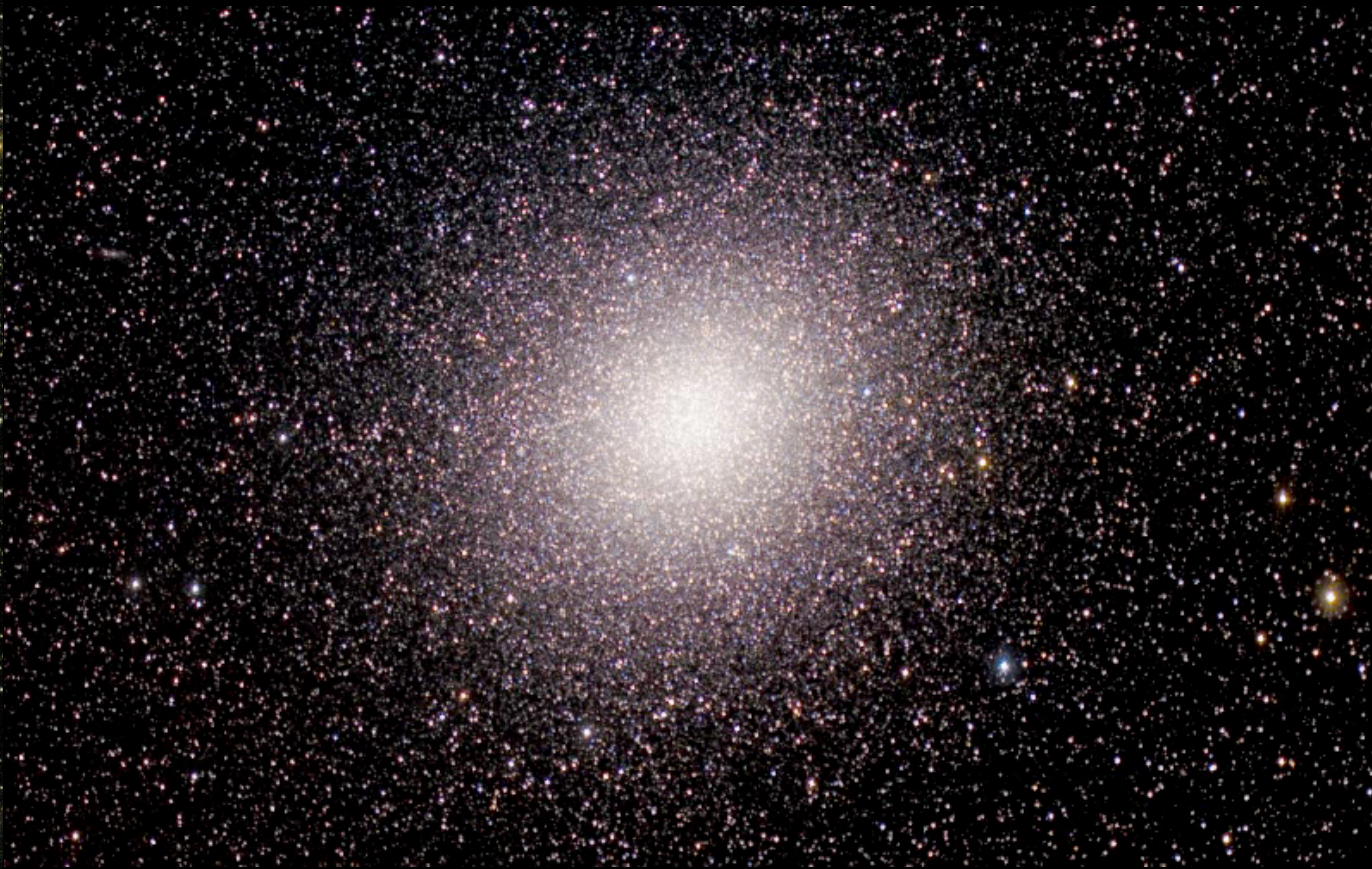


Make transformations more local

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

HST high-precision proper motions of globular clusters

- **Bonus**



Courtesy by Jay Anderson

WFI➔ACS➔WFC3➔PM

HST high-precision proper motions of globular clusters

Part I
(intro)

Part II
(techniques)

- **Part III
(the project)**

Part IV
(results)

The project

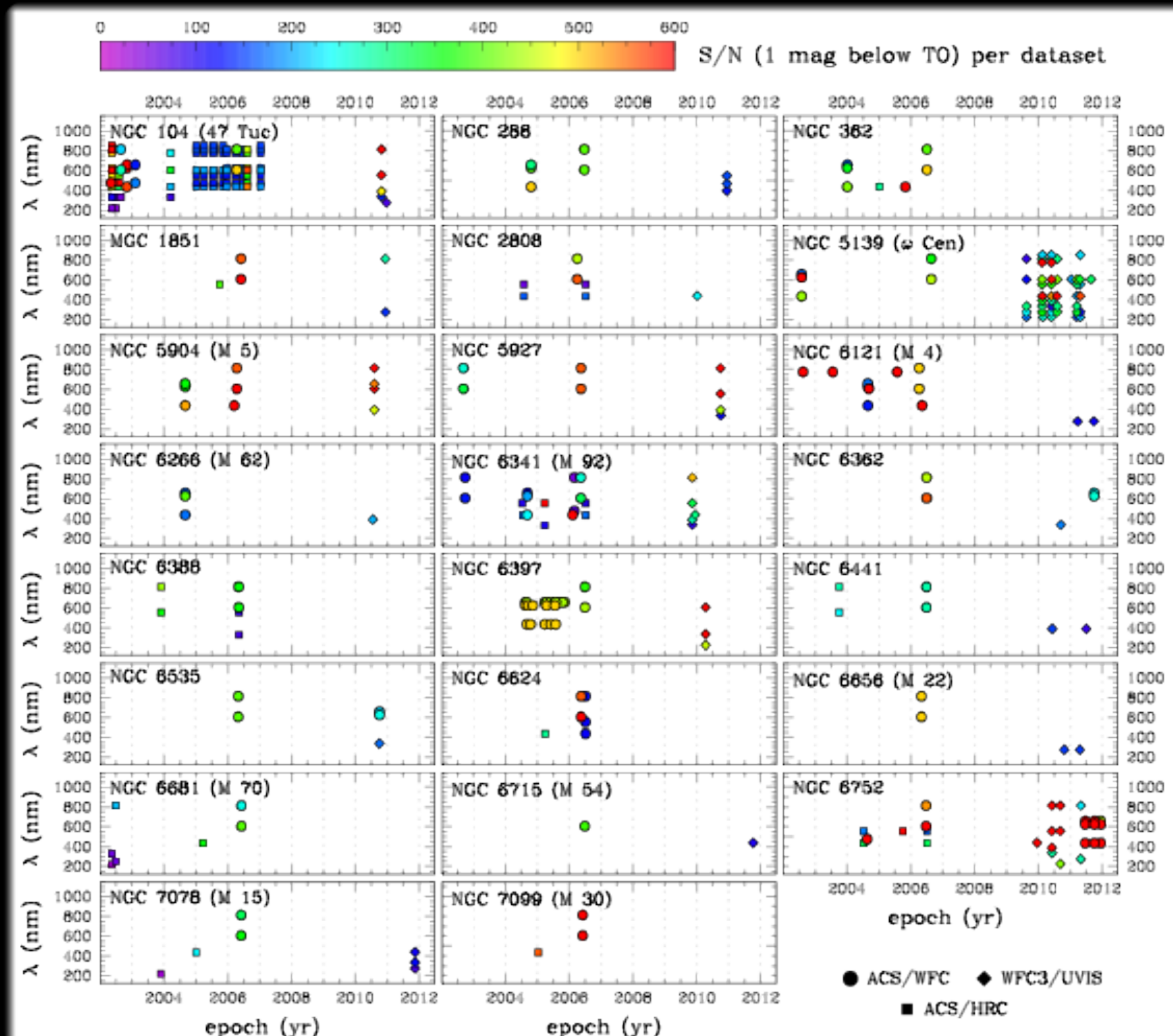
23 GCs:

4 (PI: Chandar)
4 (PI: Brown)
3 (PI: Ford)
1 (PI: van der Marel)
1 (PI: Chanamé)
10 from the archive
(PI: Bellini)

Heterogeneous datasets:

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

Homogeneous reduction



Andrea Bellini

Part I
(intro)

Part II
(techniques)

• **Part III
(the project)**

Part IV
(results)

Homogeneous reduction:

1- Need of reference frames with similar properties
2- Single-exposure catalogs obtained with the same software and procedures
3- Each star position must define a stand-alone epoch

Part I
(intro)

Part II
(techniques)

• **Part III**
(the project)

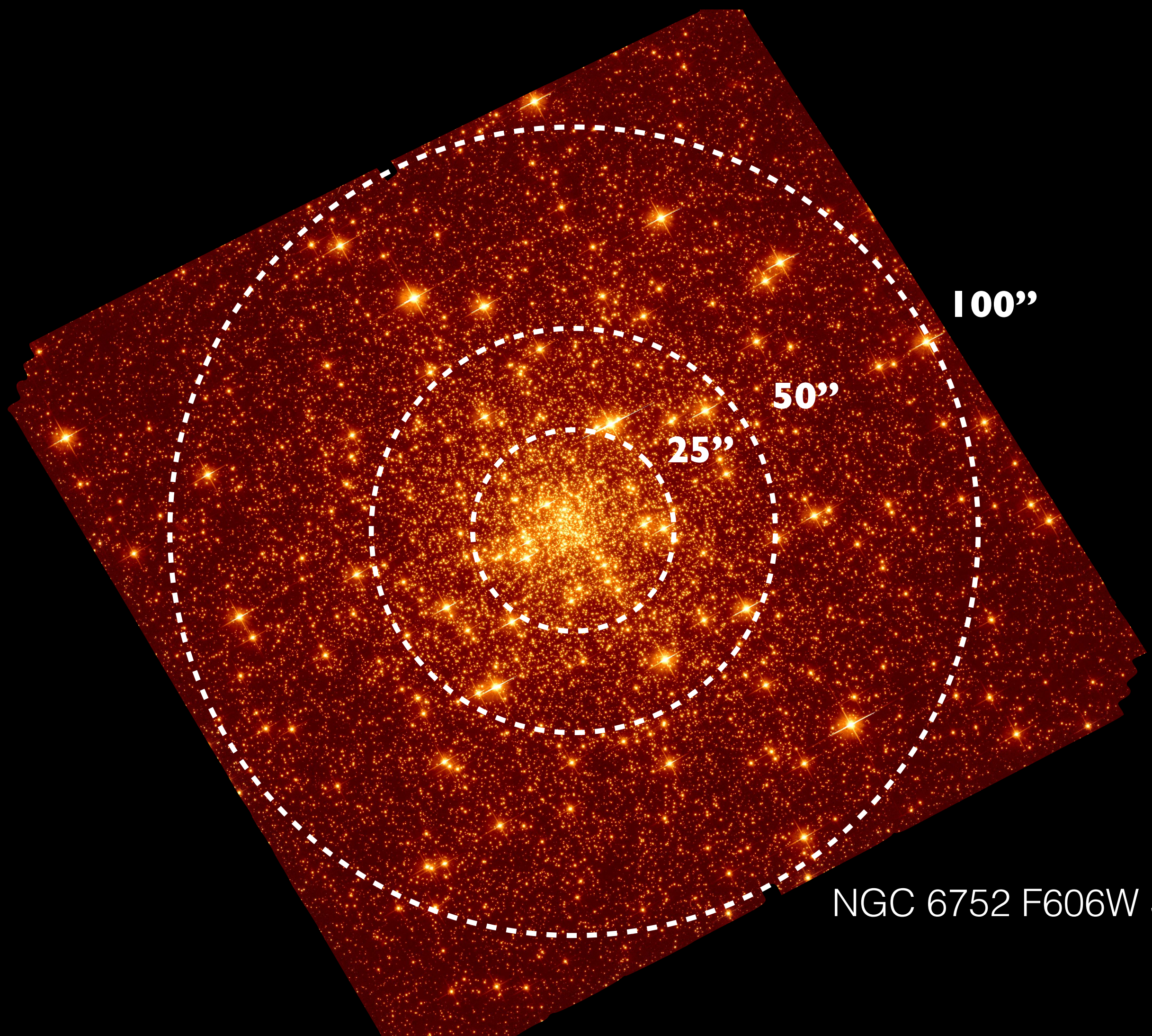
Part IV
(results)

Homogeneous reduction:

1- Need of reference frames with similar properties
2- Single-exposure catalogs obtained with the same software and procedures
3- Each star position must define a stand-alone epoch

GO-10775 GC Treasury Program (PI: Sarajedini)

- 65 MW GCs cores (central 3'x3')
- Properly-dithered exposures
- Homogeneous and deep F606W and F814W photometry
- All taken in 2006



NGC 6752 F606W Stack

HST high-precision proper motions of globular clusters

Part I
(intro)

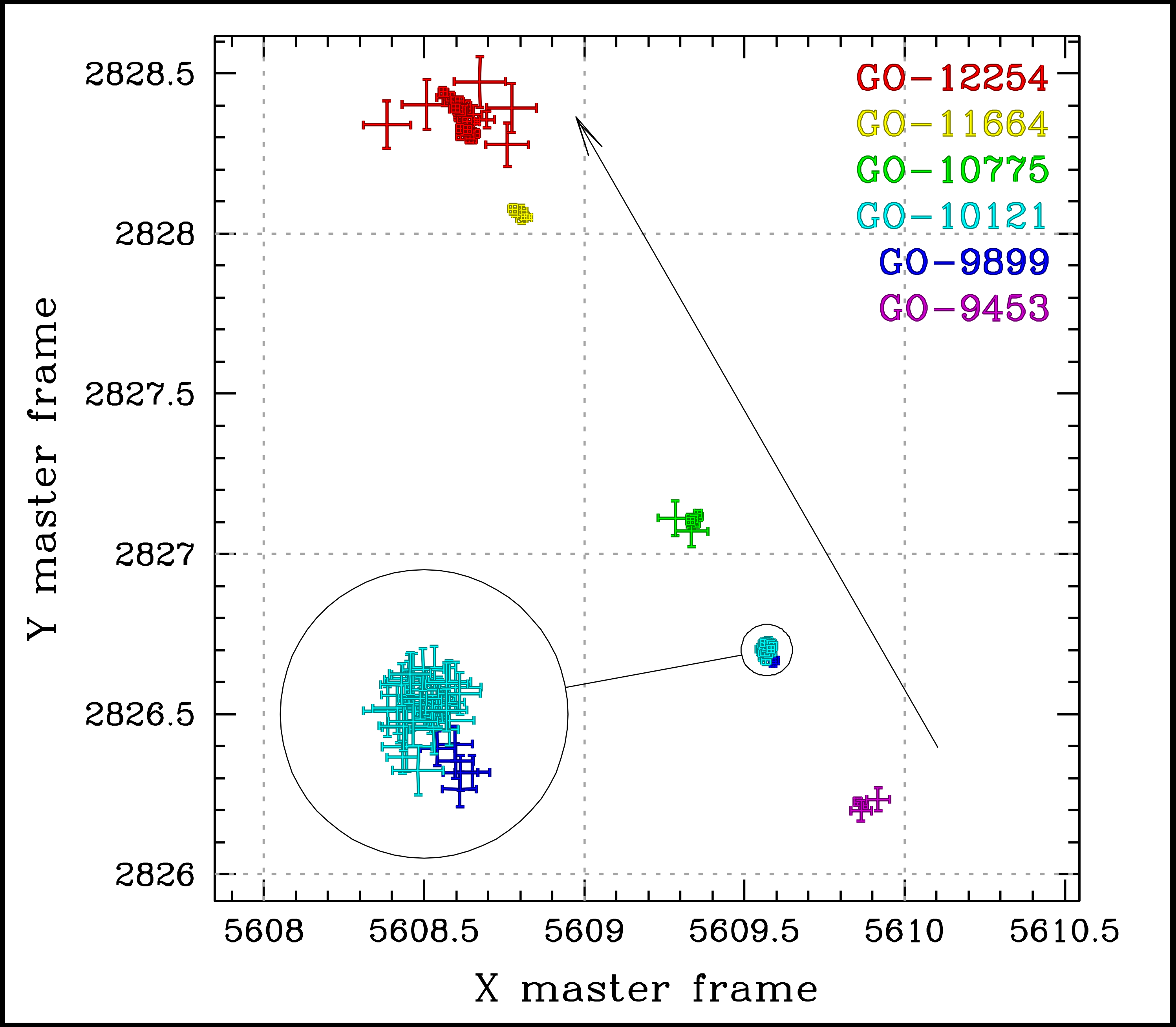
Part II
(techniques)

- **Part III**
(the project)

Part IV
(results)

Homogeneus reduction:

1- Need of a common reference frame
2- Single-exposure catalogs obtained with the same software and procedures
3- Each star position must define a stand-alone epoch



Andrea Bellini

HST high-precision proper motions of globular clusters

Part I
(intro)

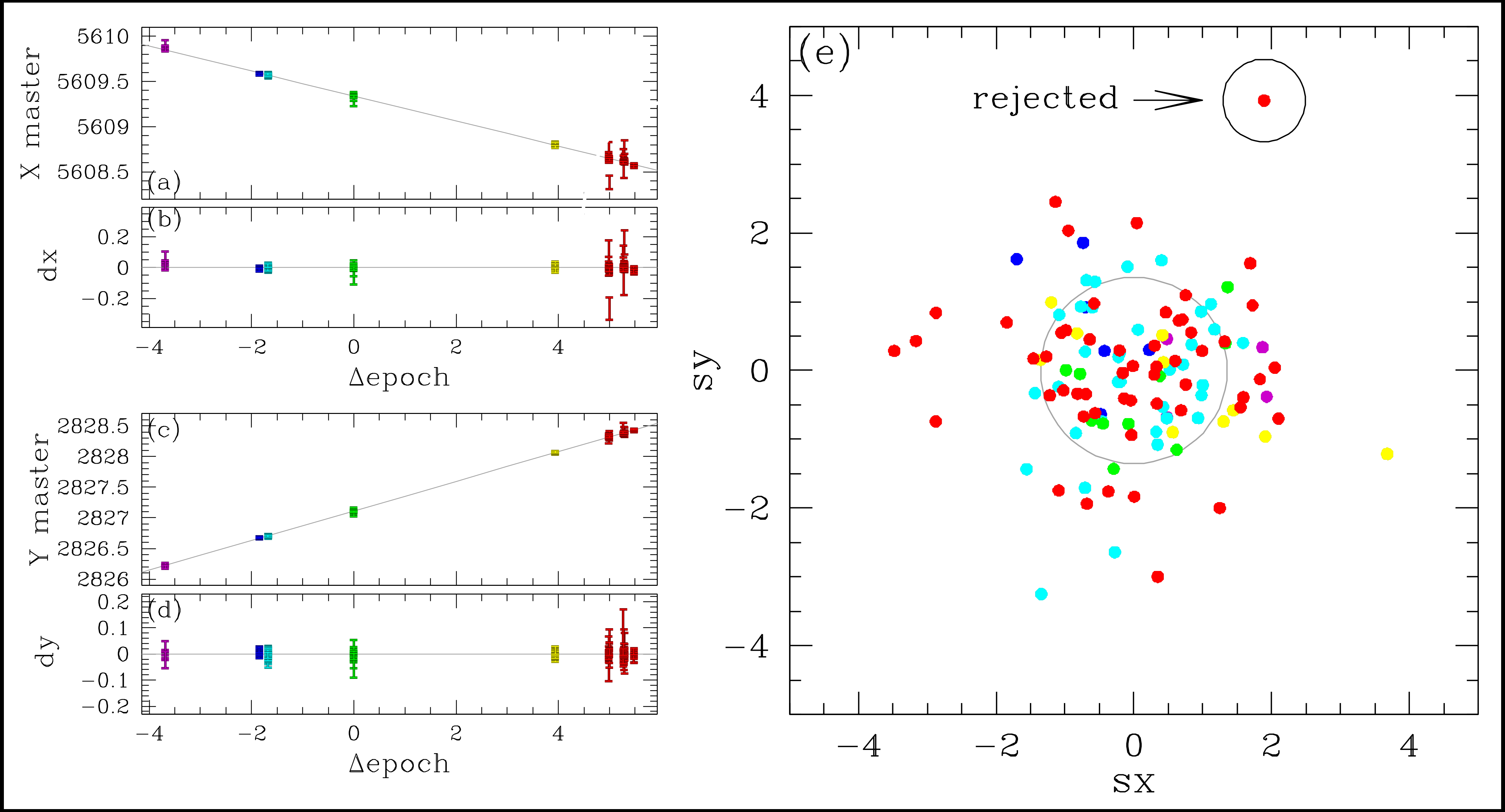
Part II
(techniques)

- **Part III**
(the project)

Part IV
(results)

Homogeneus reduction:

1- Need of a common reference frame
2- Single-exposure catalogs obtained with the same software and procedures
3- Each star position must define a stand-alone epoch



Andrea Bellini

Part I (intro)

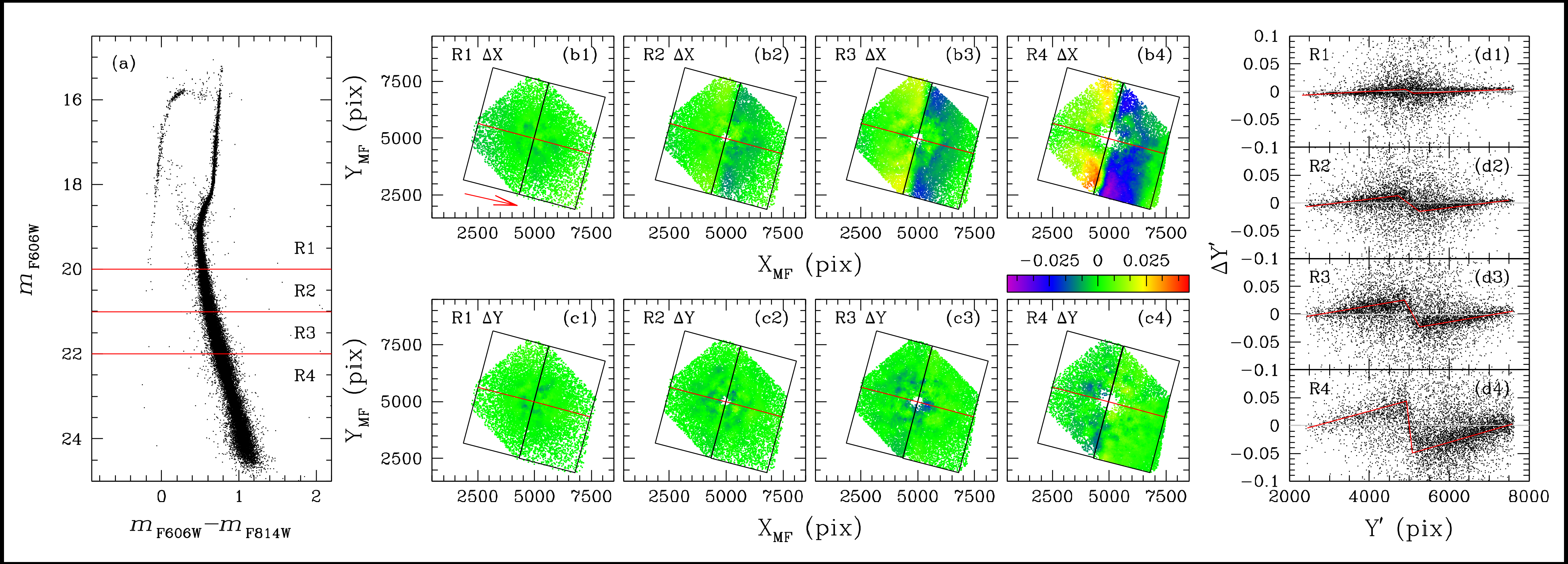
Part II (techniques)

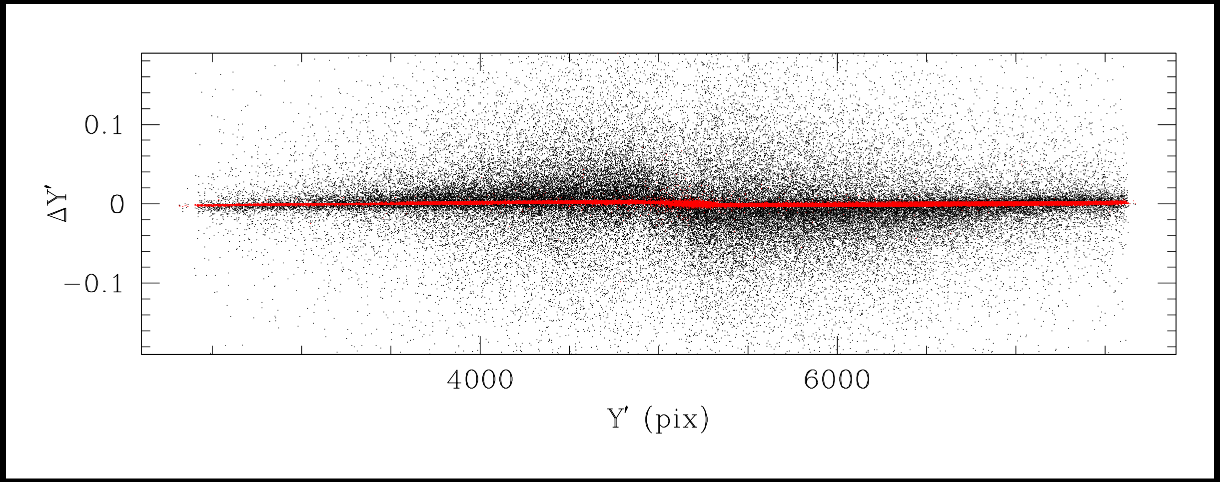
- **Part III (the project)**

Part IV (results)

Mining down systematics effects

1- The Master frame is not perfect
2- Our corrections are not perfect





Part I
(intro)

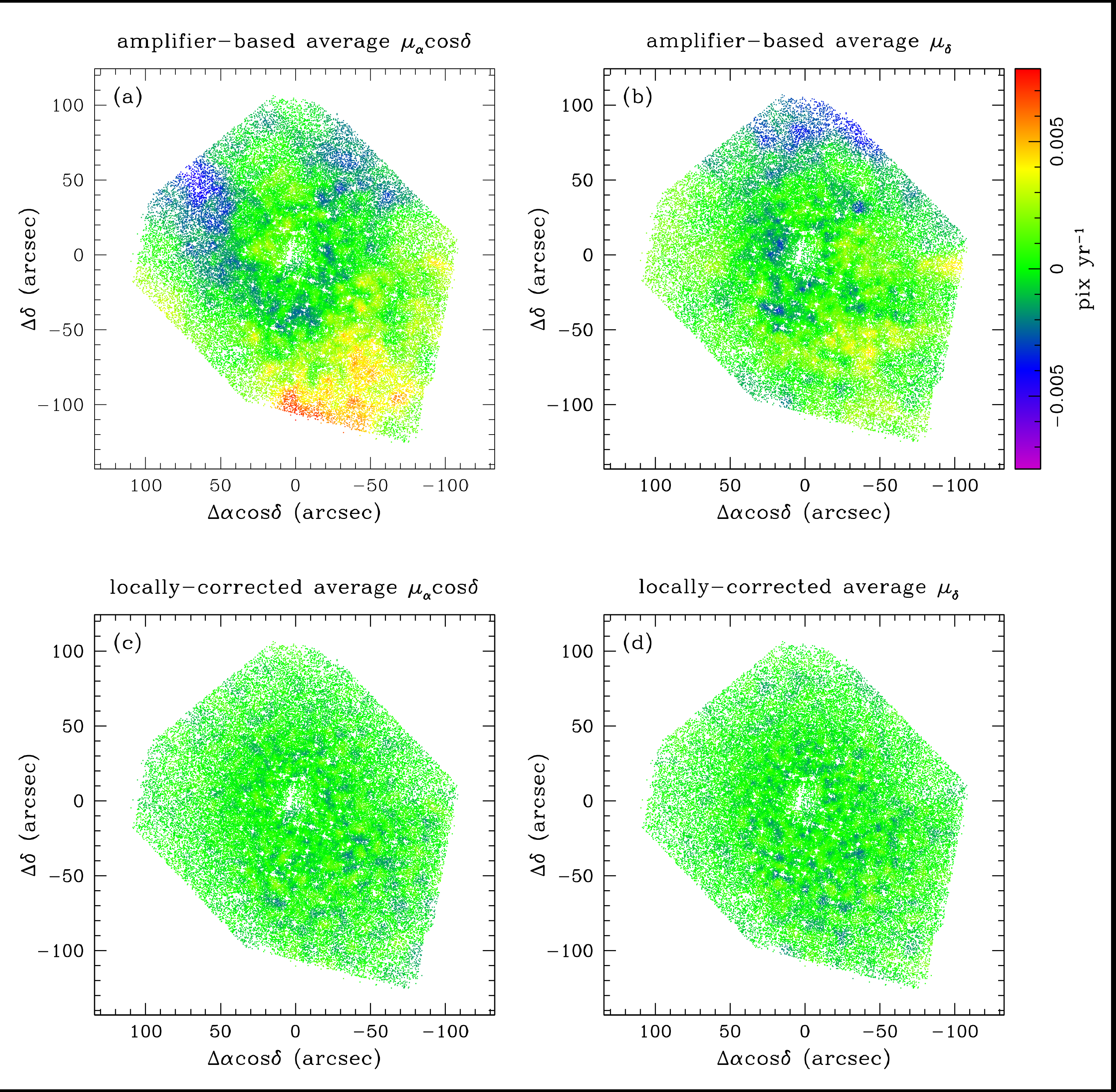
Part II
(techniques)

- **Part III (the project)**

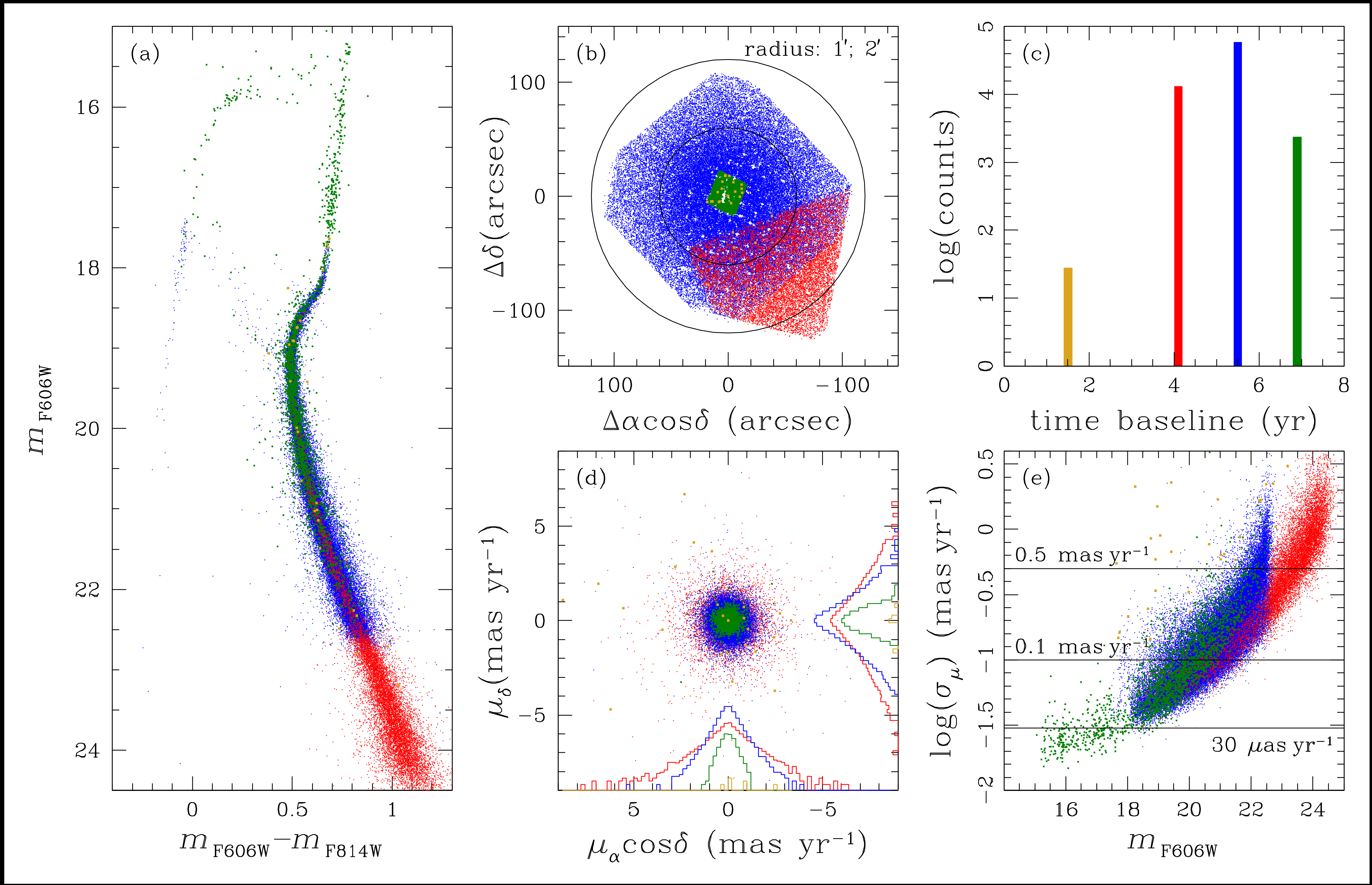
Part IV
(results)

Mining down systematics effects

1- The Master frame is not perfect
2- Our corrections are not perfect



NGC 7078 (M 15) PM Catalog overview



Bellini et al. 2014, submitted to ApJ

Part I
(intro)

Part II
(techniques)

Part III
(the project)

• **Part IV
(results)**

Part IV: Scientific results

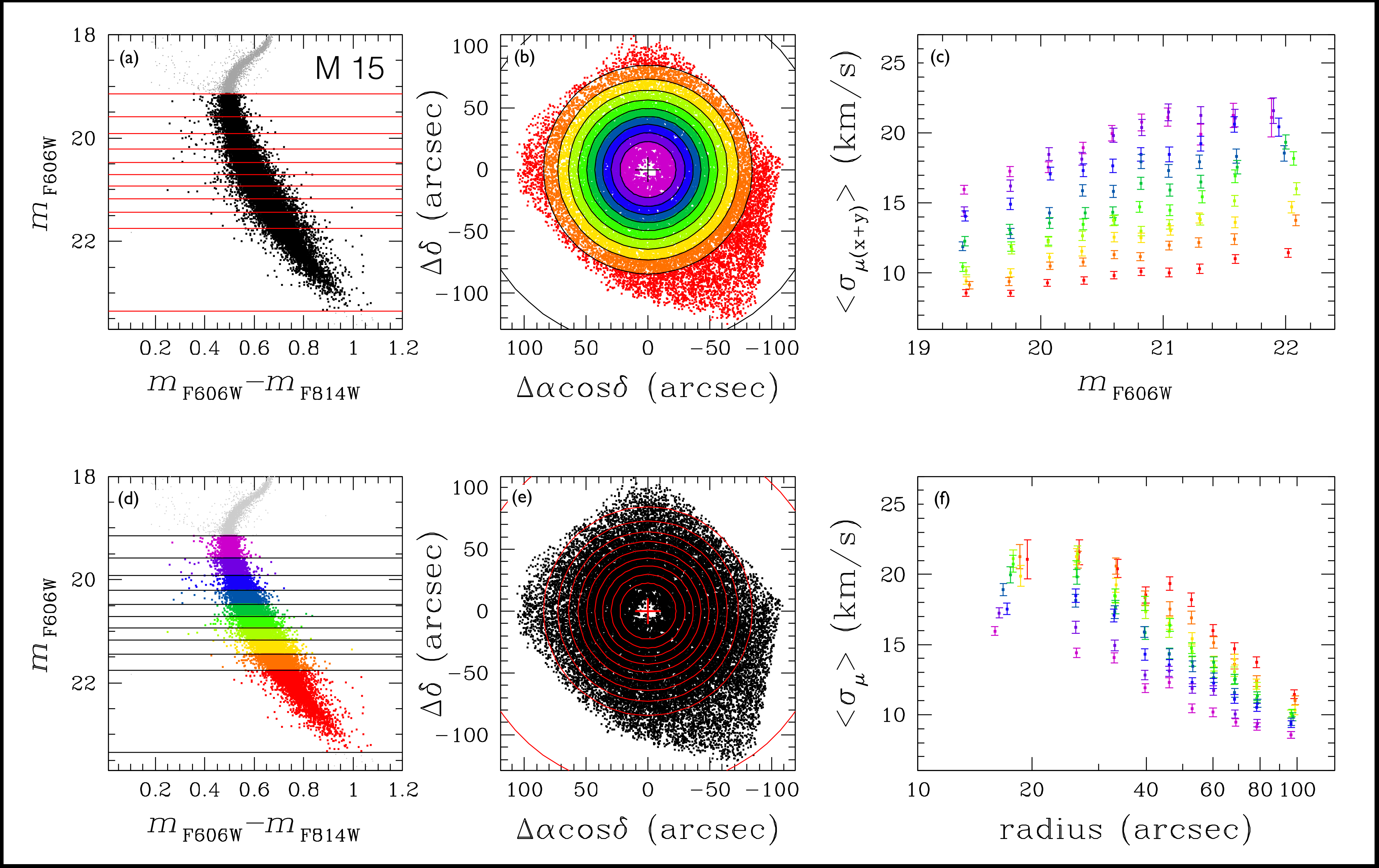
Part I
(intro)

Part II
(techniques)

Part III
(the project)

• **Part IV
(results)**

Internal motions



Bellini et al. 2014, submitted to ApJ

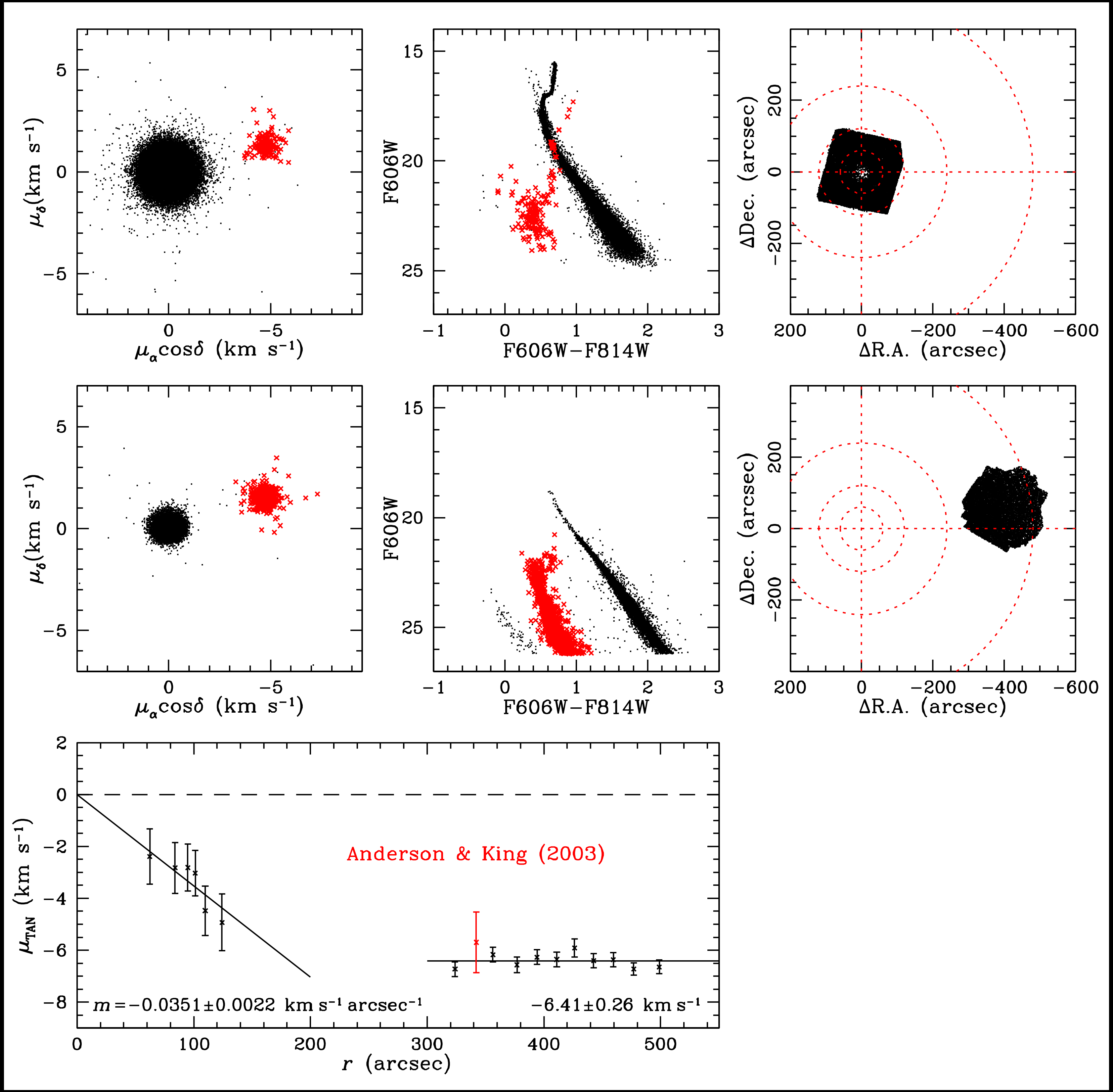
Part I
(intro)

Part II
(techniques)

Part III
(the project)

• **Part IV
(results)**

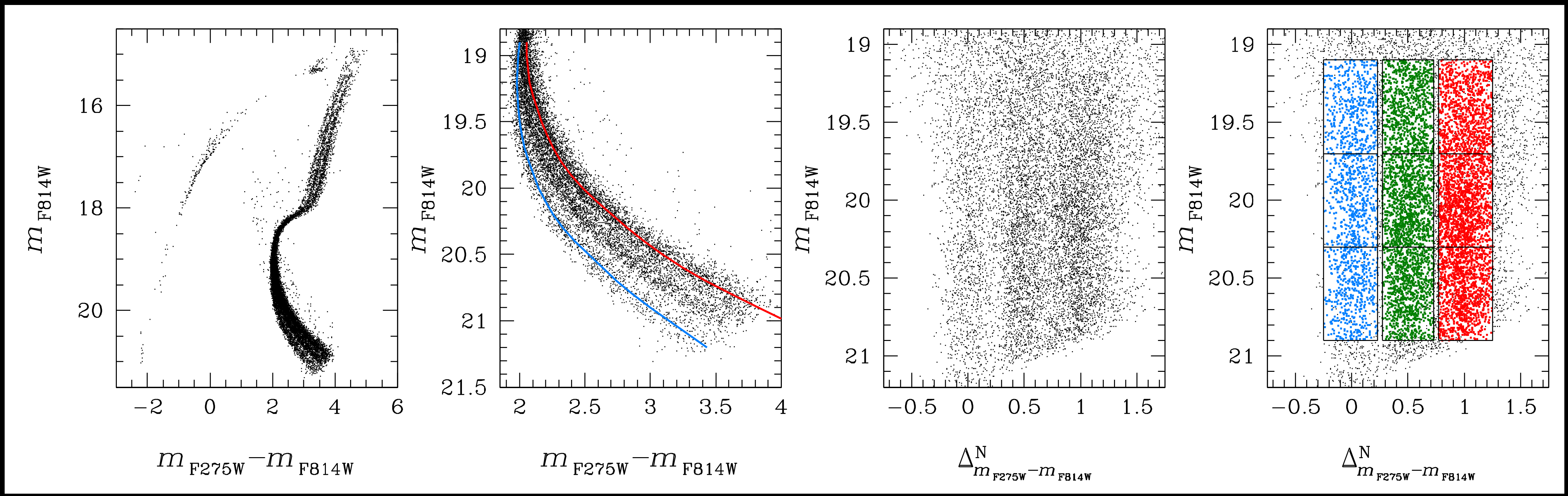
Cluster rotation (NGC 104)

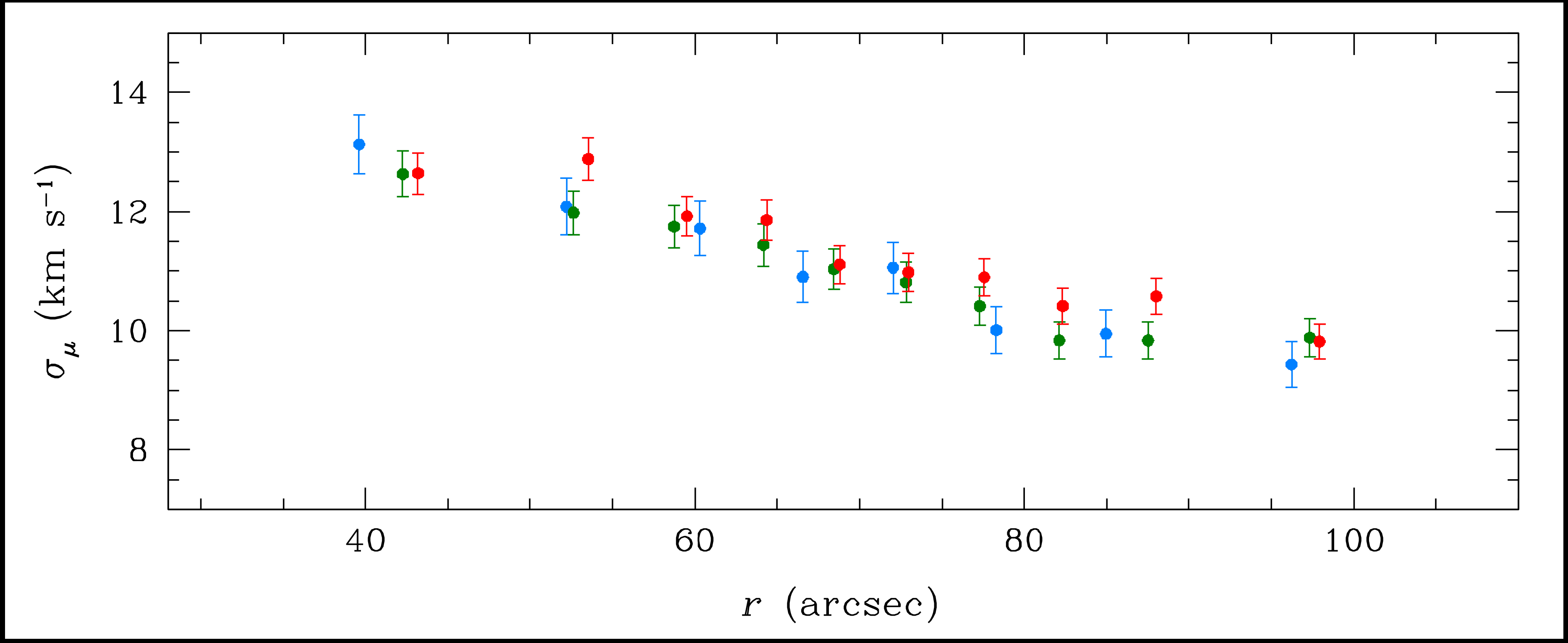


Bellini et al., in preparation

Part I
(intro)
Part II
(techniques)
Part III
(the project)
• **Part IV
(results)**

Multiple-population kinematics (NGC 2808)





Bellini et al., in preparation

HST high-precision proper motions of globular clusters

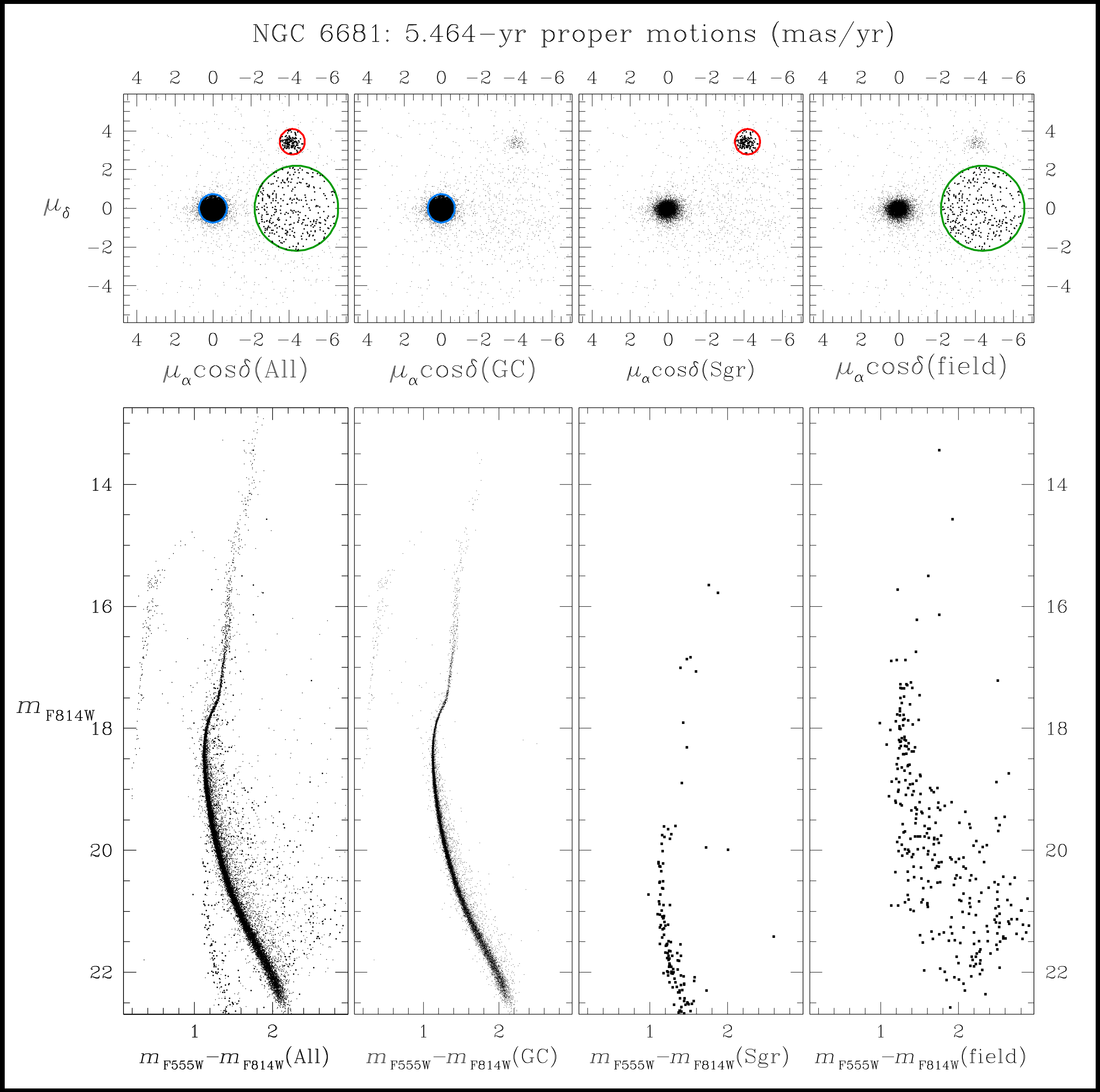
Part I
(intro)

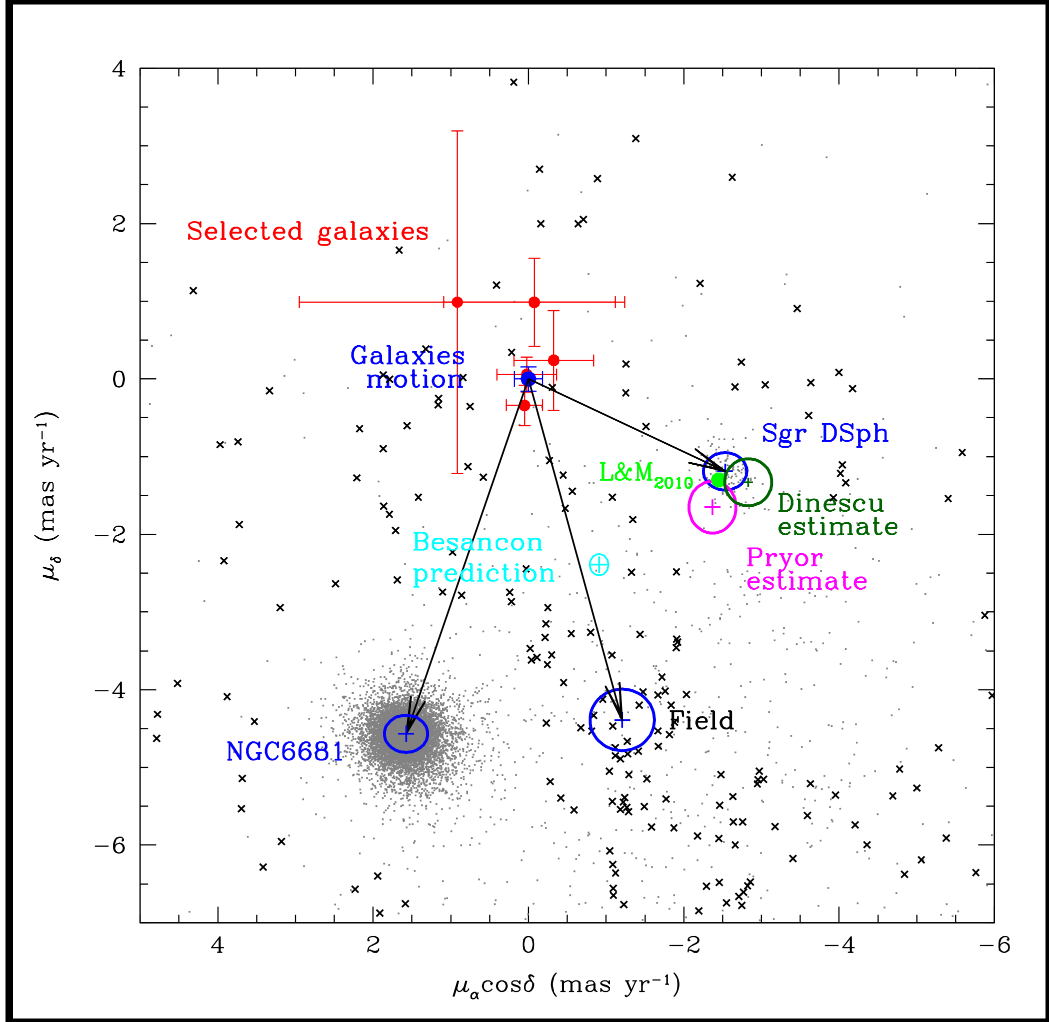
Part II
(techniques)

Part III
(the project)

- **Part IV (results)**

Absolute motion (NGC 6681)





Massari, Bellini, et al. 2013, ApJ, 779, 81M

HST high-precision proper motions of globular clusters

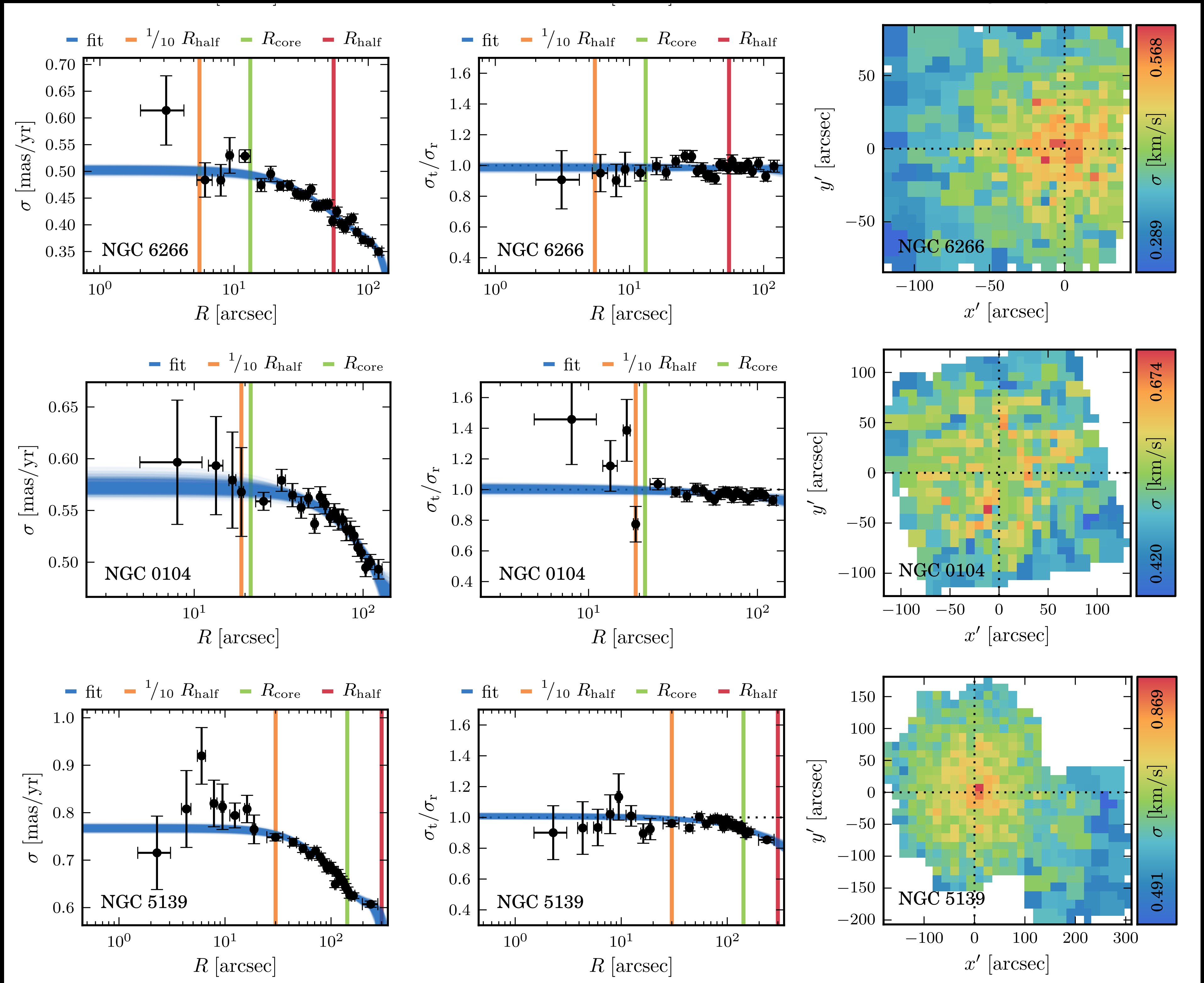
Part I
(intro)

Part II
(techniques)

Part III
(the project)

- **Part IV (results)**

Dispersion profiles / (An)isotropy



Watkins L. L., Bellini A., et al., in preparation

HST high-precision proper motions of globular clusters

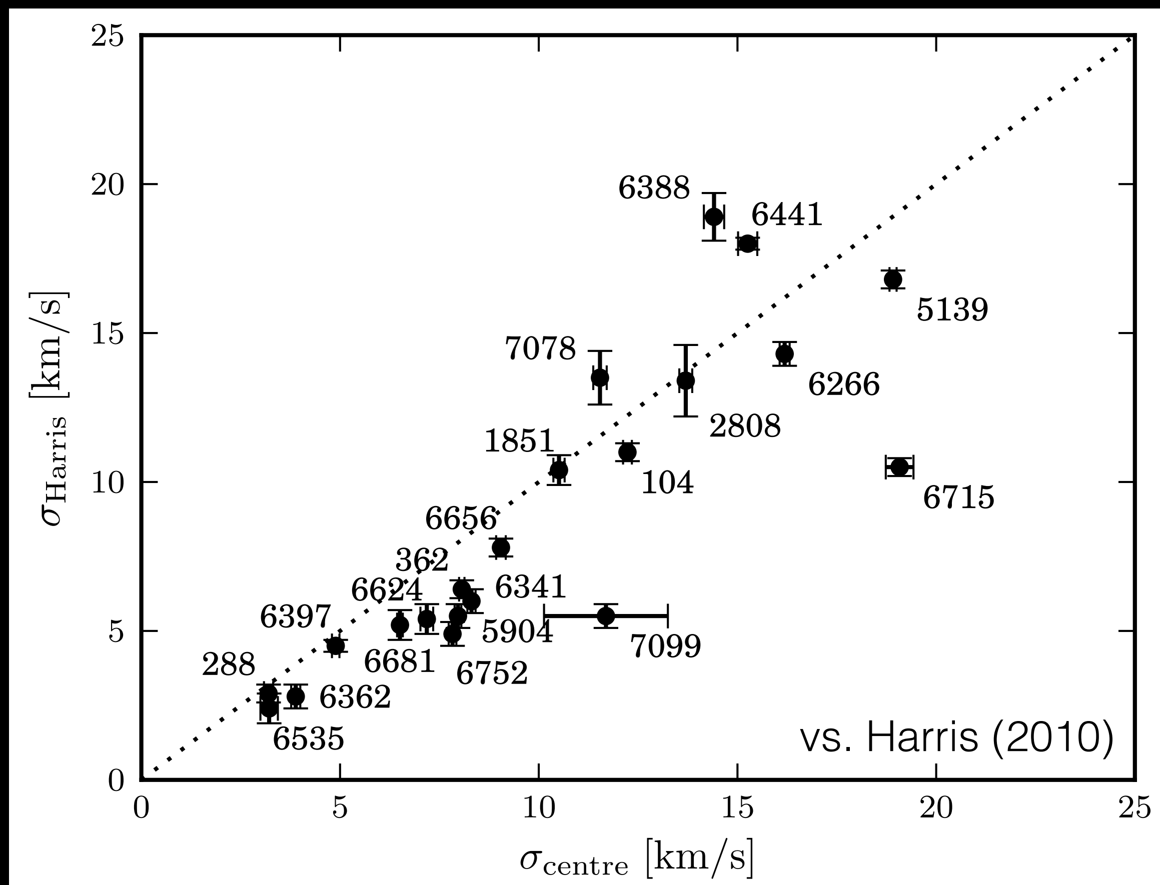
Part I
(intro)

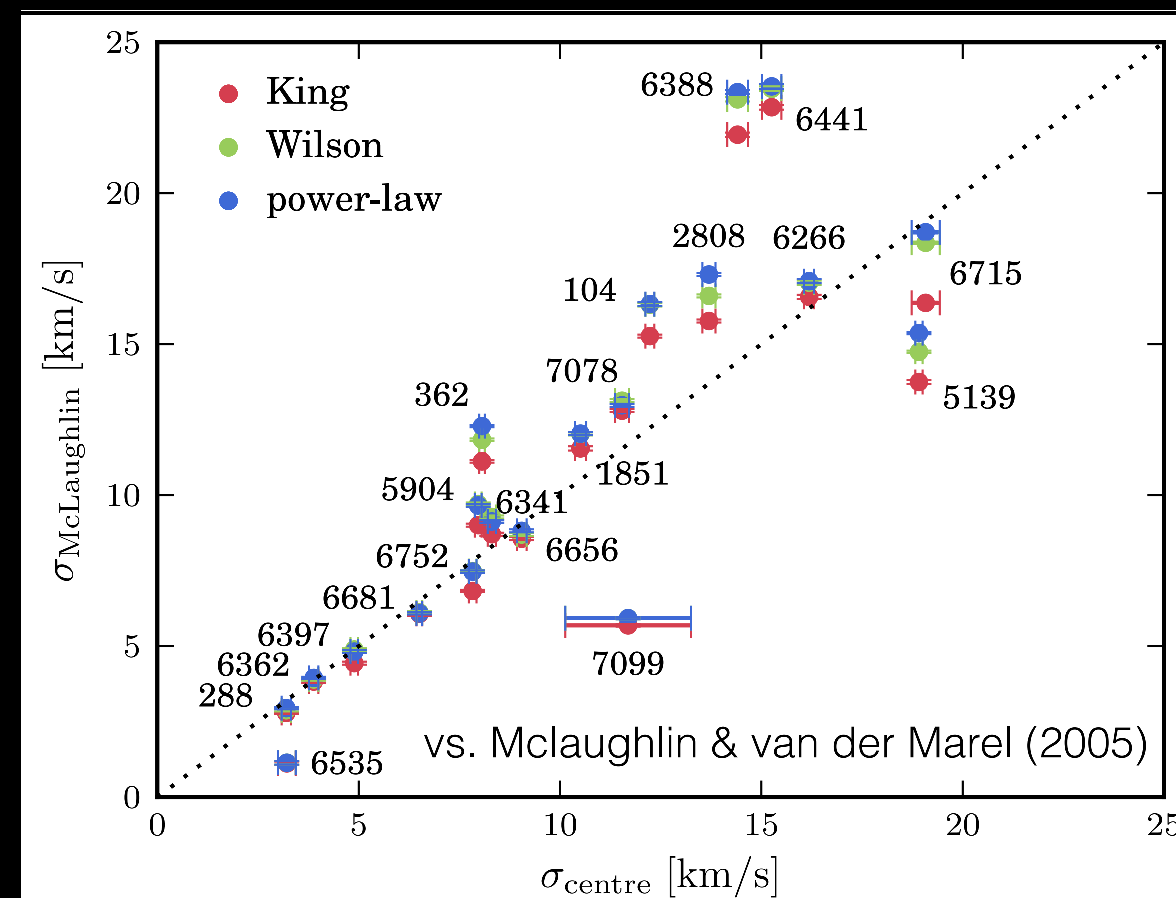
Part II
(techniques)

Part III
(the project)

- **Part IV (results)**

Vanilla distances





Watkins L. L., Bellini A., et al., in preparation

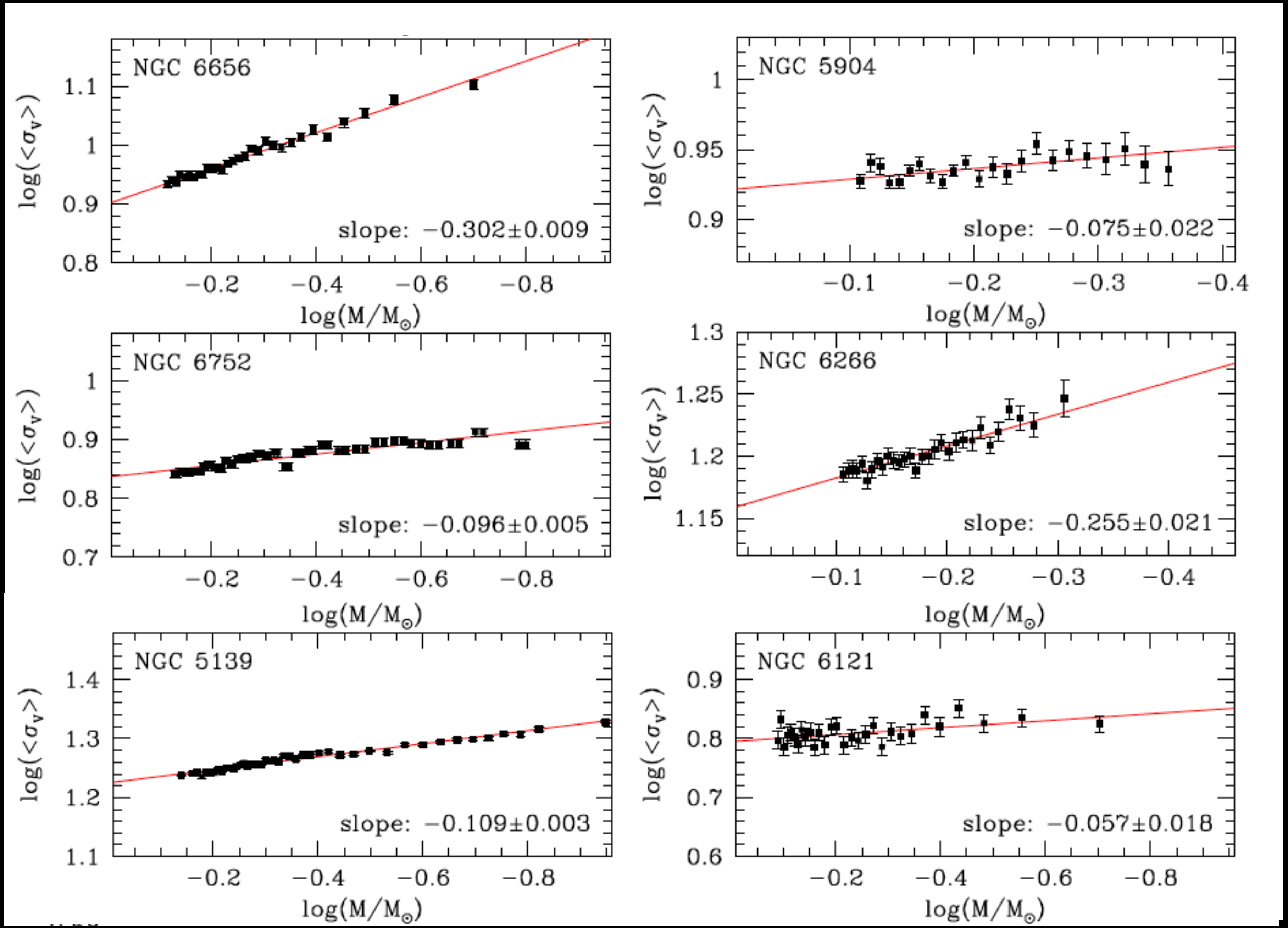
Part I (intro)

Part II (techniques)

Part III (the project)

• **Part IV (results)**

Equipartition (?)



Conclusions

High-precision astrometry with *HST is* challenging but DOABLE

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

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

- Internal kinematics
- dispersion profiles
- anisotropy
- rotation
- IMBHs
- …

Our project

- high-precision (~1 km/s) proper motions in the cores of 22+ GCs
- preliminary results encouraging and exciting
- proper-motion catalogs will be made available to the astronomical community
- Future extension to 60+ GCs thanks to new observations