HST Proper Motions in the Cores of Globular Clusters

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Workshop on the Dynamics of
Low-Mass Stellar Systems
Santigo, Chile
April 6, 2011

Clipper Adventurer

Penguins on Glacier

Mountain Reflections

Blue Icebergs

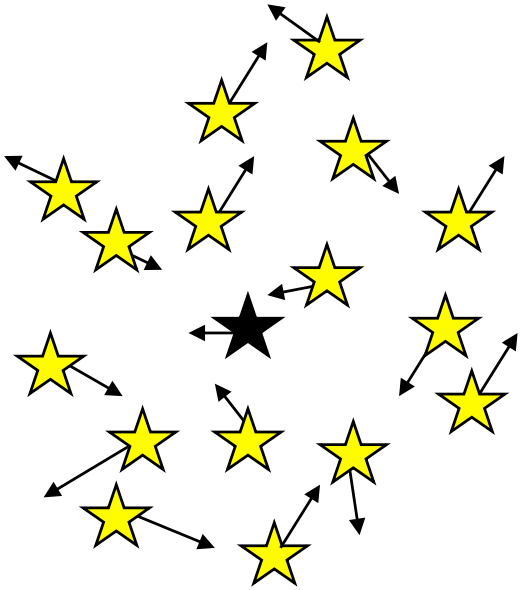
Civilization!

Organization of Talk

- **PMs with HST**
- **Update on ω Centauri**
- **Work in progress**
  - NGC 6752, NGC6341, NGC2808
- **Future work**

PMs with HST

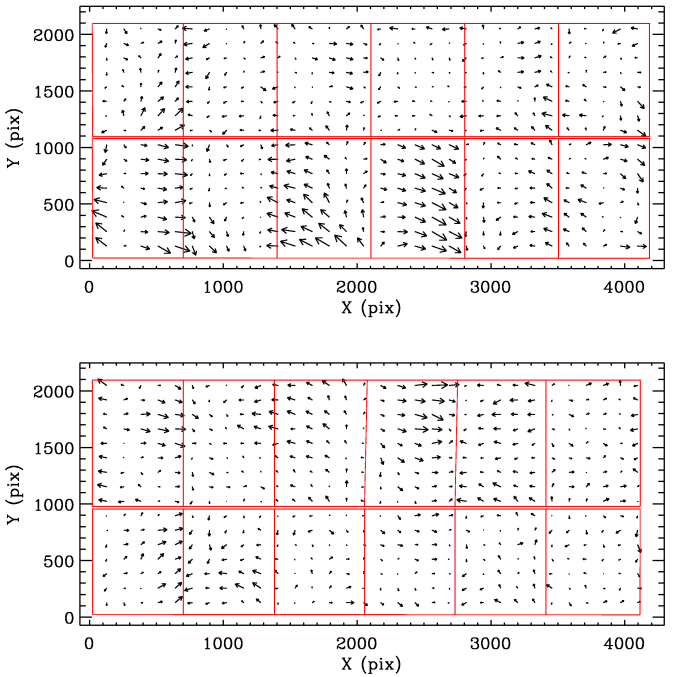
- **All astrometry is differential**
  - N can be from 50 to 200,000
  - PMs can be absolute, though!



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

- **Advantage: stability, strehl**
  - GB: Seeing, chromatic, isoplanatic patch
  - HST: Only breathing

- **Complexities**
  - Distortion (~400 pixels!)
  - Undersampling:
    - Almost all cameras
    - Good PSF models, measuring software
  - CCD Irregularities: WFPC2, ACS, WFC3…
  - CTE… (a correction! See Anderson & Bedin 2010)
  - Breathing: ~ 0.01 pixel



Bellini, Anderson, Bedin 2011

Current HST PM Pr

Membership

- Faint WDs
- Stars at H-burning limit

Internal motions in cores of GCs

- IMBHs?
- Distances: $\sigma_{PM} \longleftrightarrow \sigma_{RV}$
- Cluster models (anisotropy, equipartition, pop studies…)
- Rotation

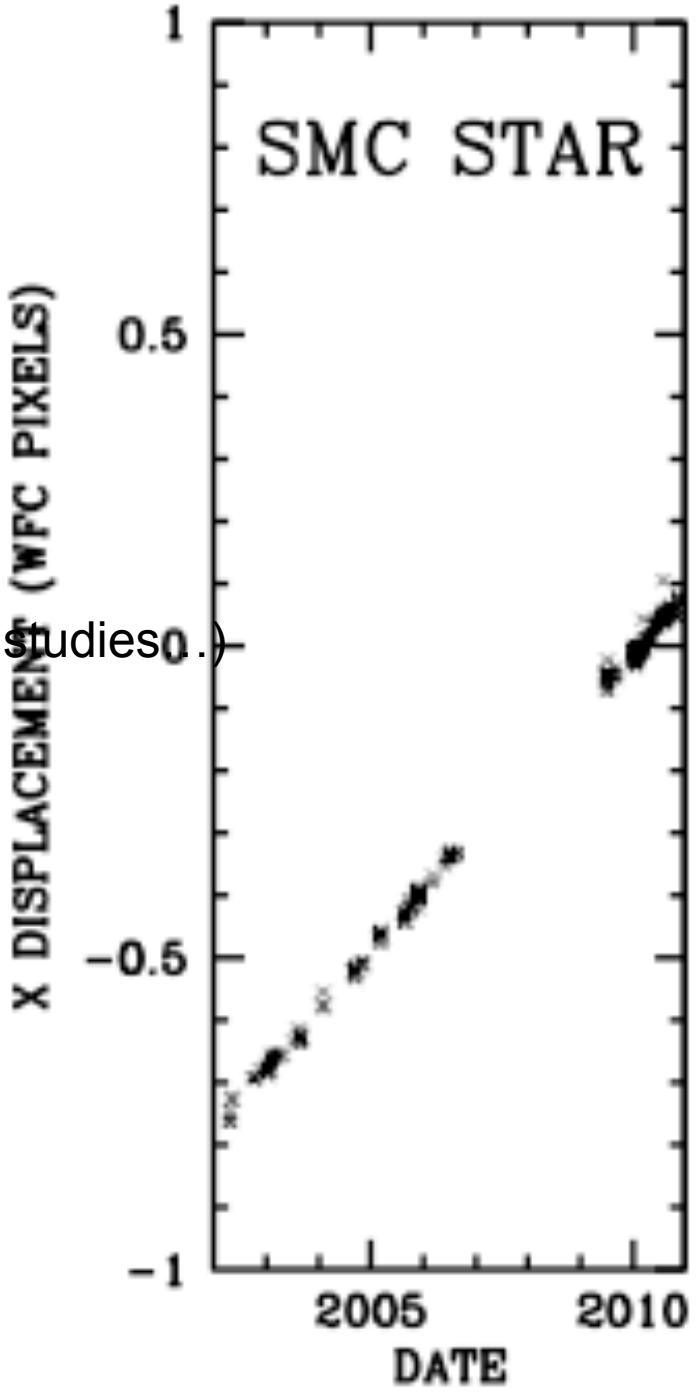
Absolute PMs

- Globular clusters
- DSphs
- Even M31…

Parallaxes

- Field neutron stars
- 47T (with respect to the SMC)

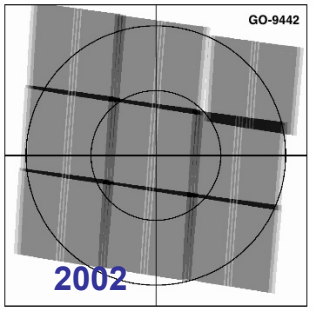
ASK ME!

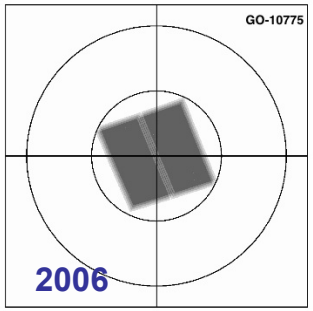


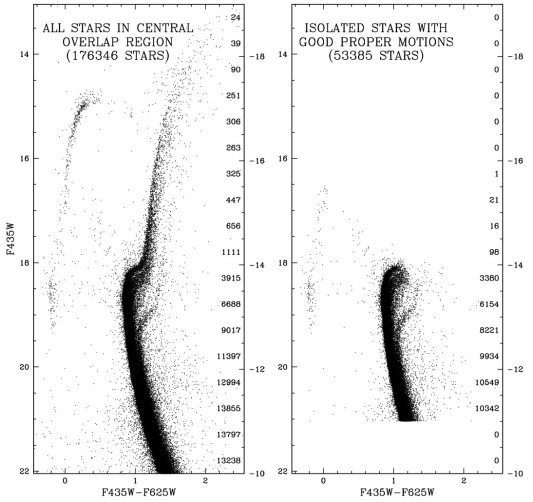
PMs in ω Cen

Motions in AvdM10

- 4-year baseline
- Catalog of 50,000 stars in core
  - No bright/faint (limited by 2006-epoch)
  - 100 good within 3.5″

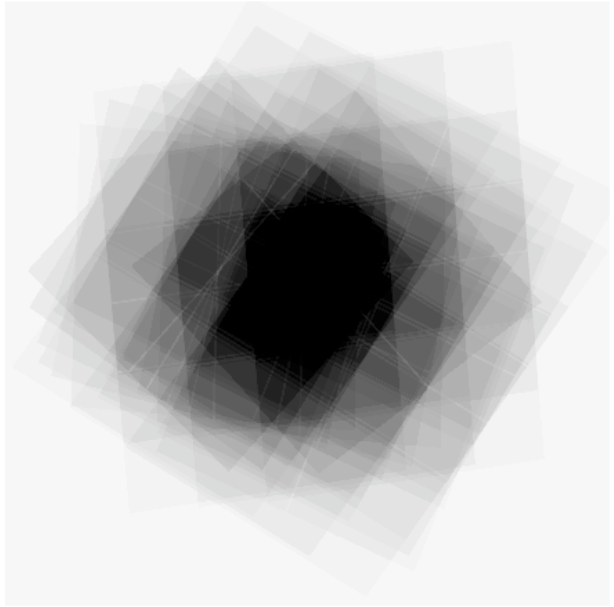


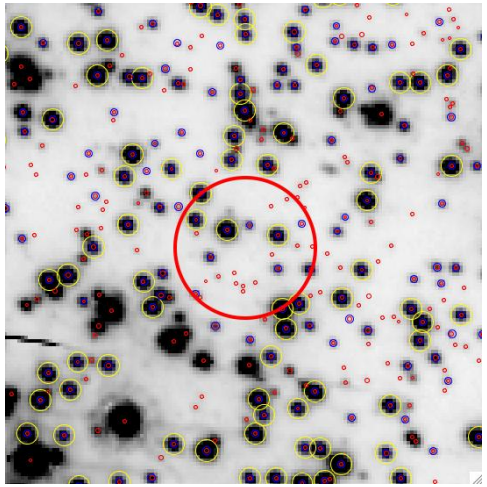


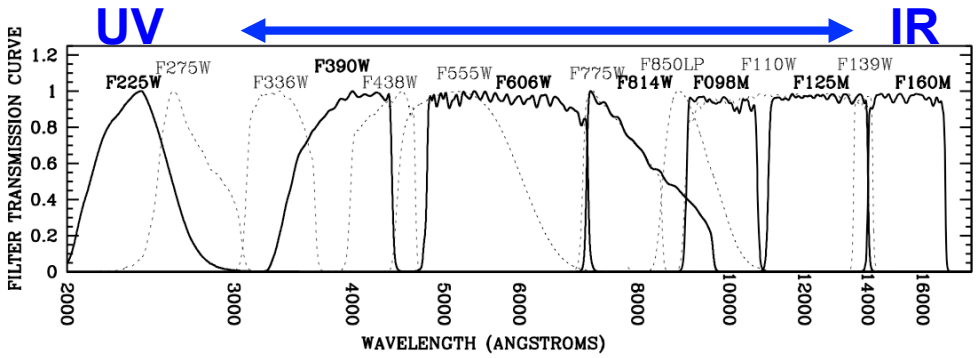


More observations!

- **WFC3 Calibration field**
  - 333+ indep UVIS exposures
    - 8+ year baseline
    - >10 visits, orients
    - Wide dithers
    - 15 filters: UV to IR
- **New catalog to come:**
  - Bright + faint stars
  - More precision -vs- More stars
  - **Will again make completely public**

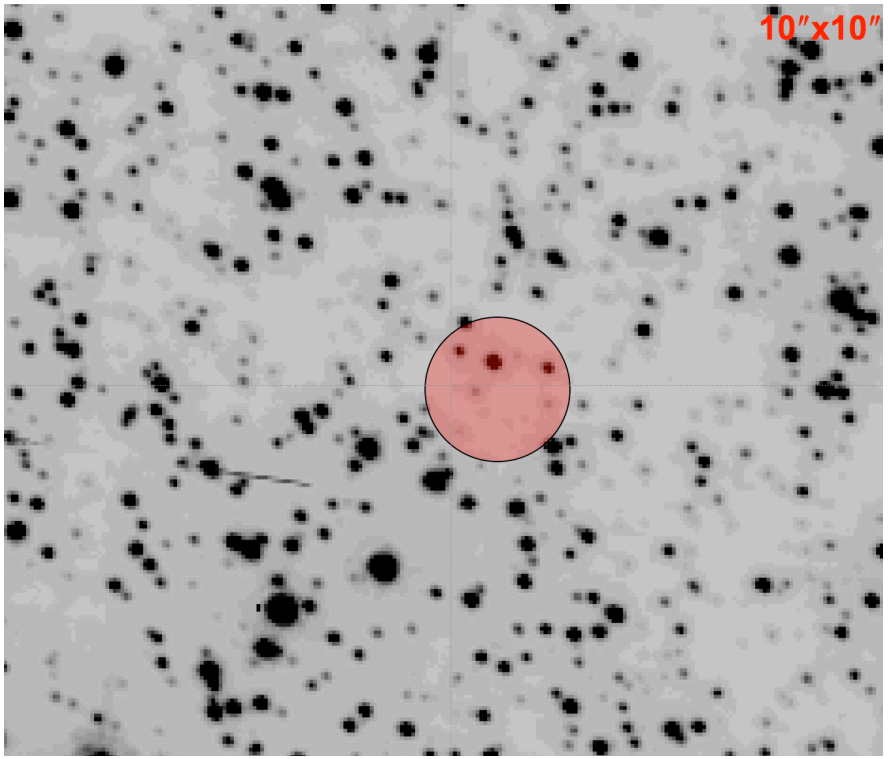


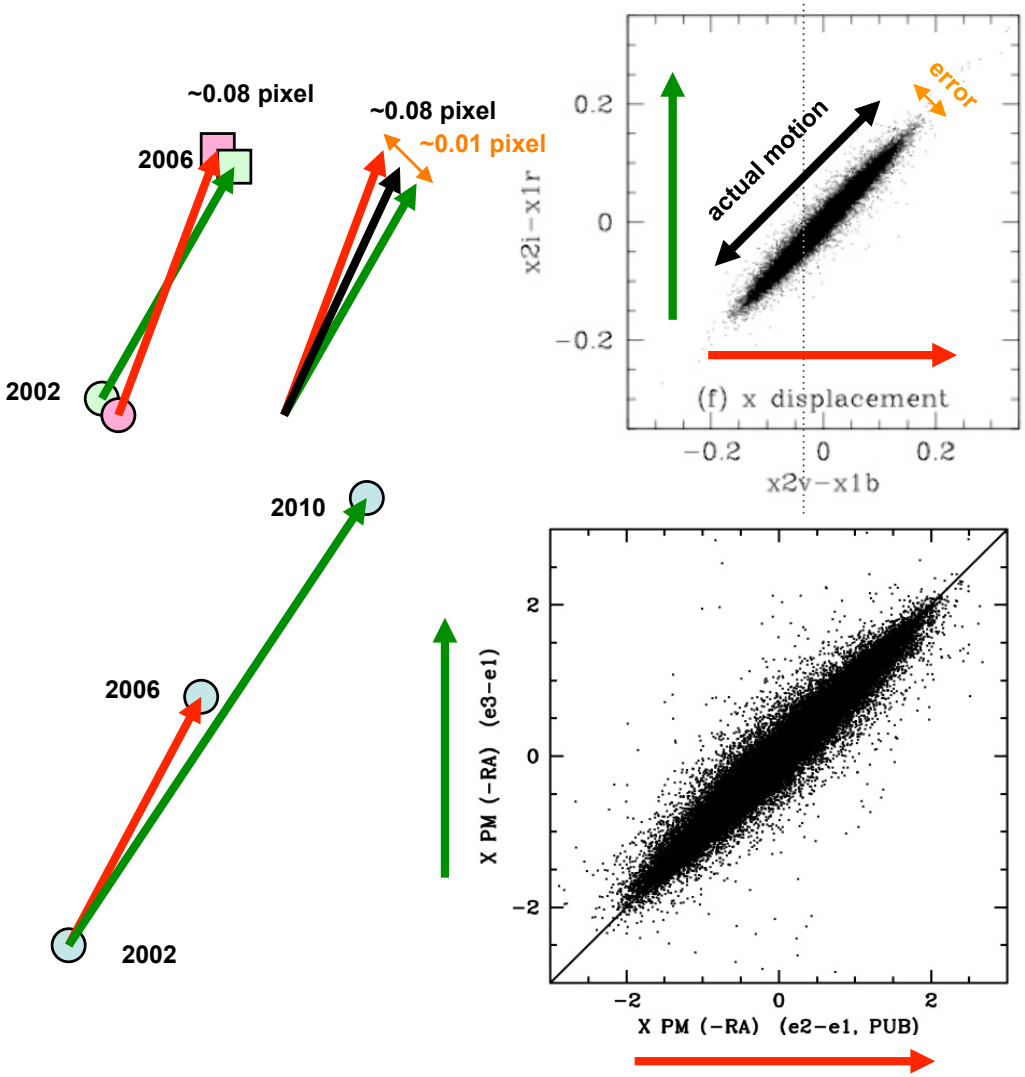




Validating the PMs

- **Motions in AvdM10**
  - Errors from half-samples
    - e1a to e2a
    - e1b to e2b
- **New test… 3 epochs**
  - Completely independent





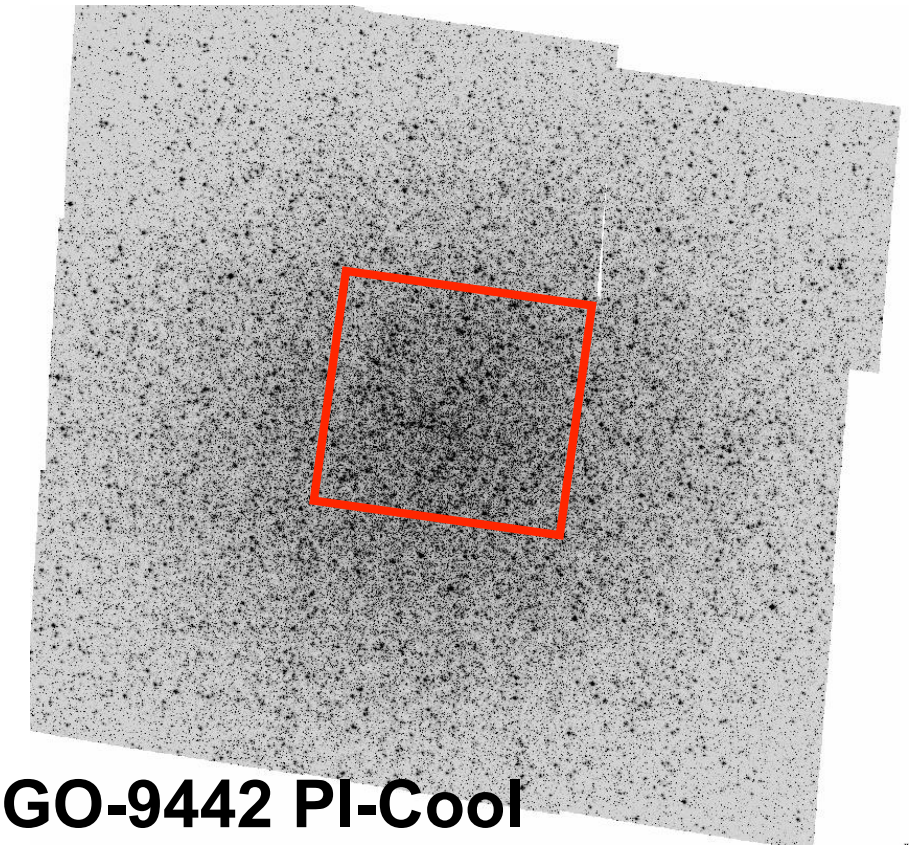
Excellent agreement for all 50,000+ stars!

ω Centauri

Huge IMBH, or maybe none at all?

- **Noyola et al. 08 found:**
  - (1) Cluster center from an ACS image inside core
  - (2) Cusp in Surface-Brightness Profile (**SBP**)
  - (3) RV dispersion increase in central IFU (5″×5″)

~40,000 $M_\odot$ IMBH



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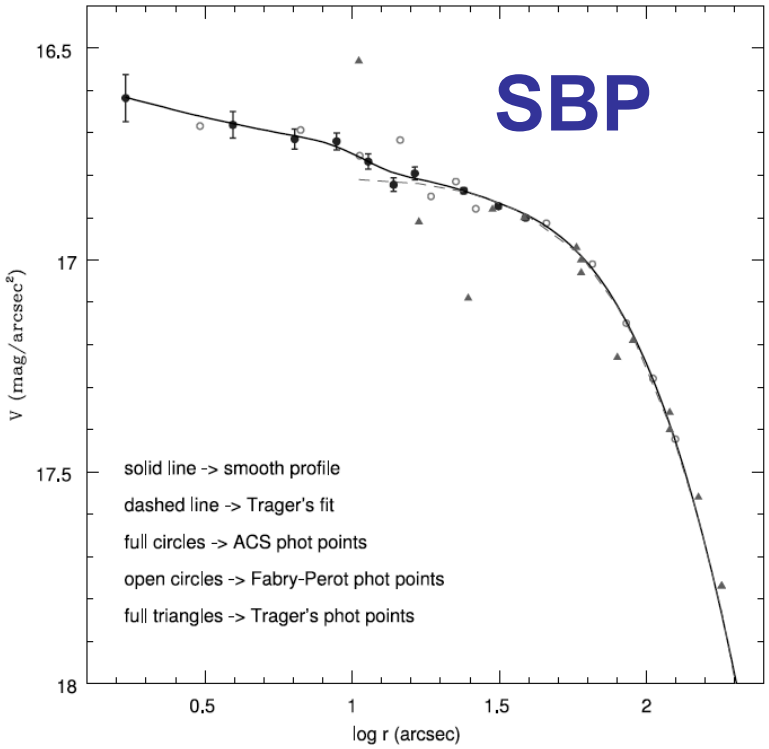
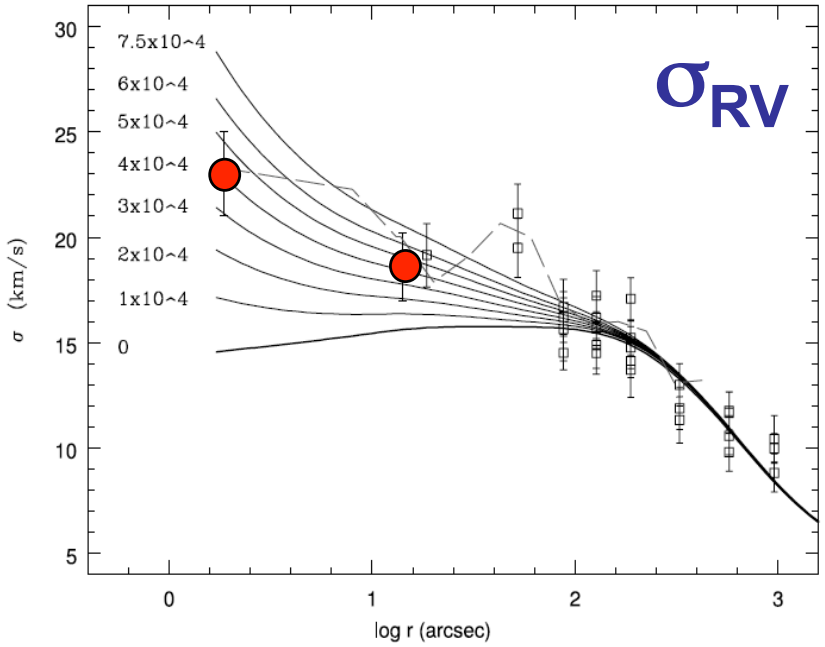


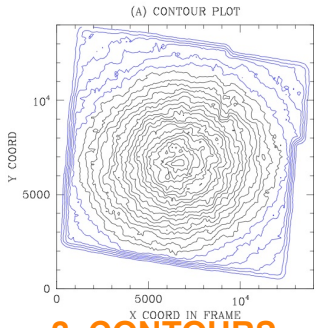


ω Centauri

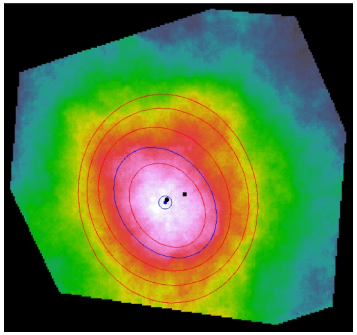
1. PIE SLICES

Huge IMBH, or maybe none at all?

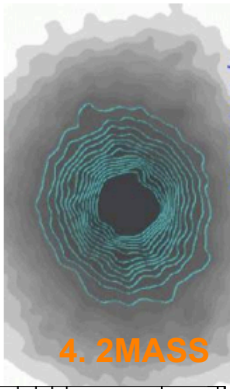
- **Noyola et al. 08 found:** → ~40,000 $M_\odot$ IMBH
- **AvdM10 & vdMA10 found:**
  - (1) Center: 1M-star catalog
    - → 4 ways **agree to 2″** ; 10 ApJ pages… + Goldsbury et al 2010
    - → center off by 12″ from NGB08/historic center (<10% of R_c)
  - (2) Number Density Profile: **NDP** not biased by giant PSF haloes
    - → **No cusp** needed
    - → *Fundamental* limitation
  - (3) PMs for 50,000 stars in core
    - → ***No*** fast-moving stars, at either center (Drukier & Bailyn 2003)
    - → ***No*** dispersion increase within ~ 30″
    - → Also found (1) Slight radial anisotropy (2) G-H moments
    - (3) No central rot'n (4) **Not** in equipartition



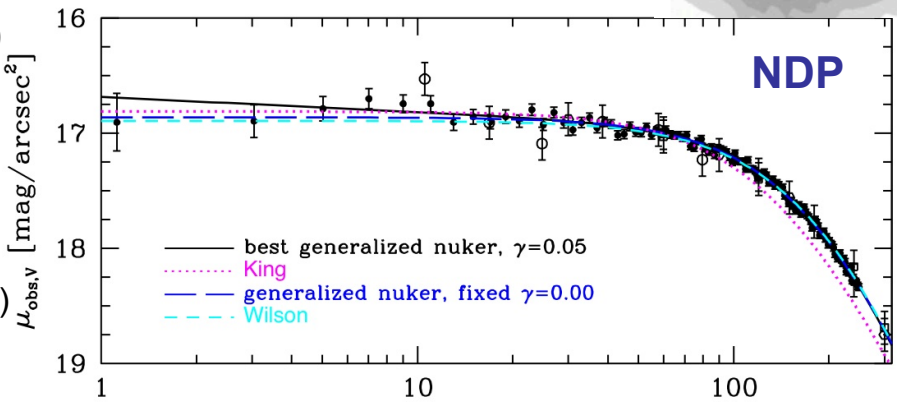
2. CONTOURS



3. PM σ



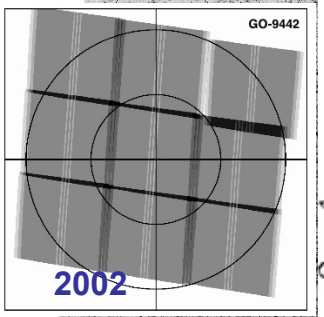
4. 2MASS

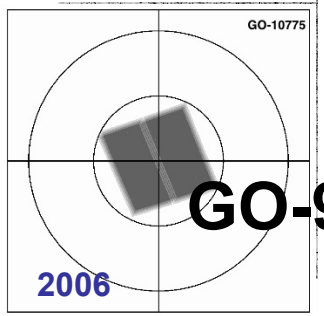


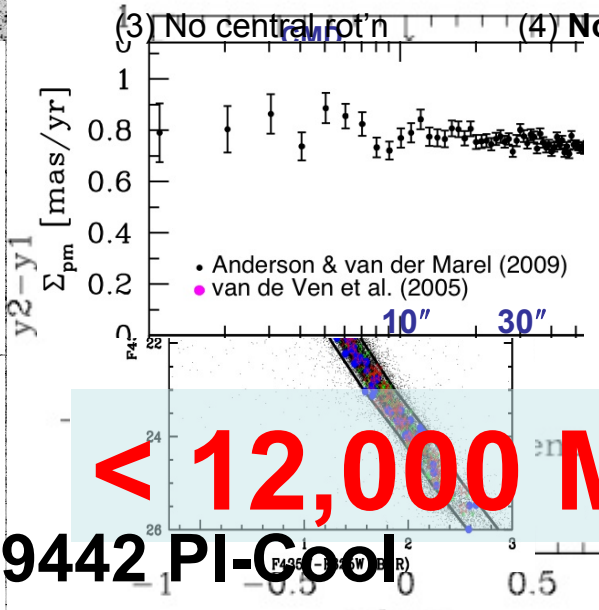
ALL STARS

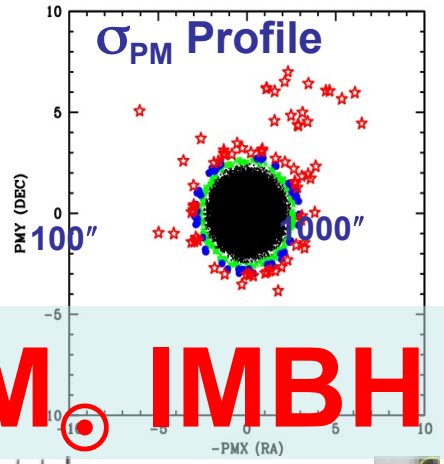
MEMBER MOTION

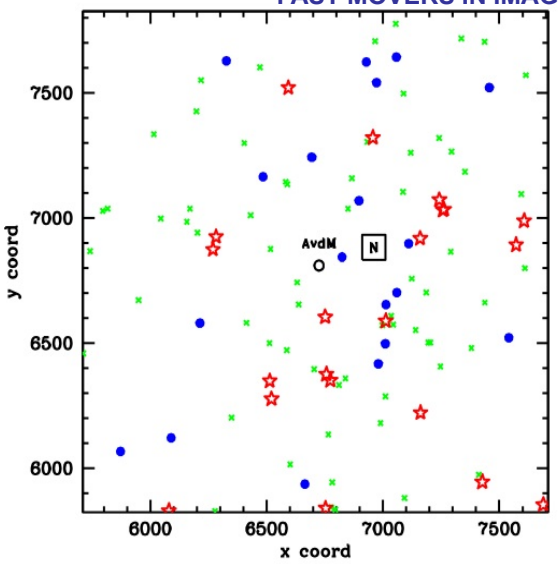
FAST MOVERS IN IMAGE

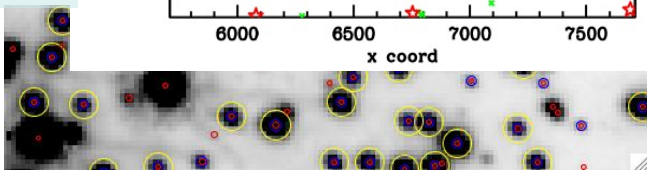












< 12,000 $M_\odot$ IMBH

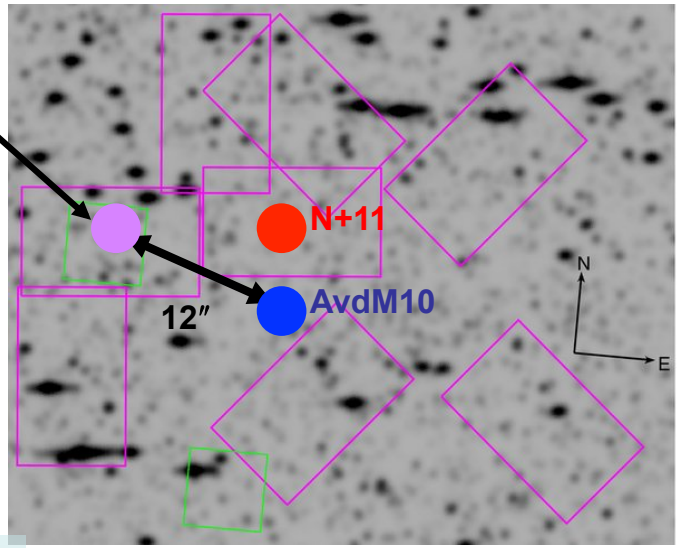
GO-9442 PI-Cool

10′ × 10′

ω Centauri

Huge IMBH, or maybe none at all?

- **Noyola et al. 08 found:** **~40,000 $M_\odot$ IMBH**
- **AvdM10 & vdMA10 found:** **< 12,000 $M_\odot$ IMBH**
- **Noyola et al. 11 found:**
  - New center; more symmetric RV distn



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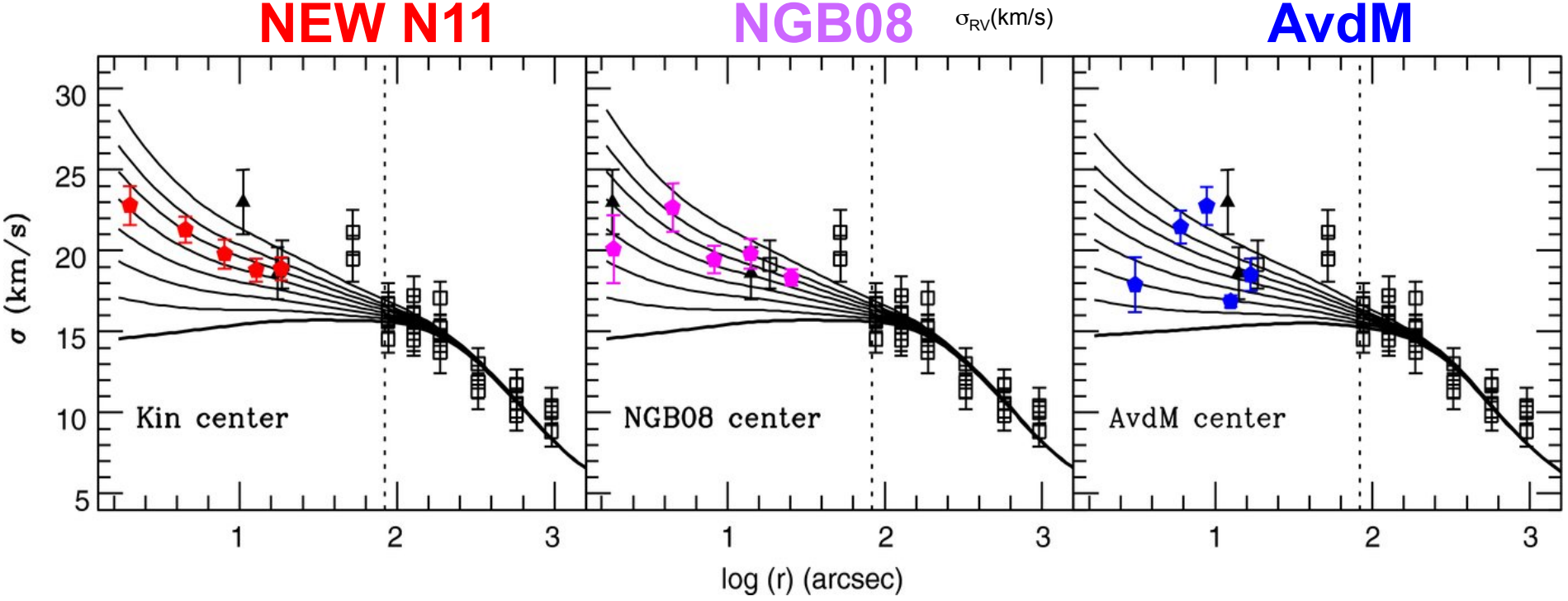

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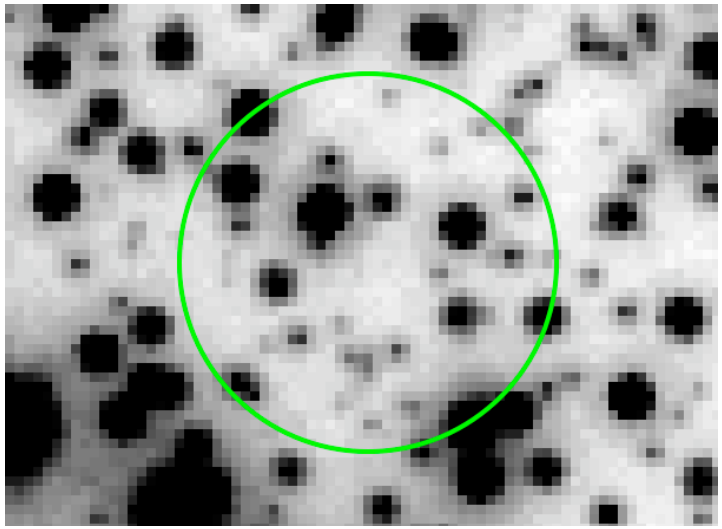


Minor Points of Disagreement: Models

	RV Effort	PM Effort
Center	Spatial/Kinematic offset	Spatial/PM-Kinematic coincide to 2″ → Only centers with errorbars
Σ Profile SURFACE DENSITY	Assume cusp	NDP consistent with being flat → **Cusps in these models lead to bigger IMBH**
Isotropy	Assume isotropic	We measured 5% radial (intrinsic) → **Ignoring anisotropy can lead to bigger IMBH**

Difference ~ 15,000 $M_\odot$

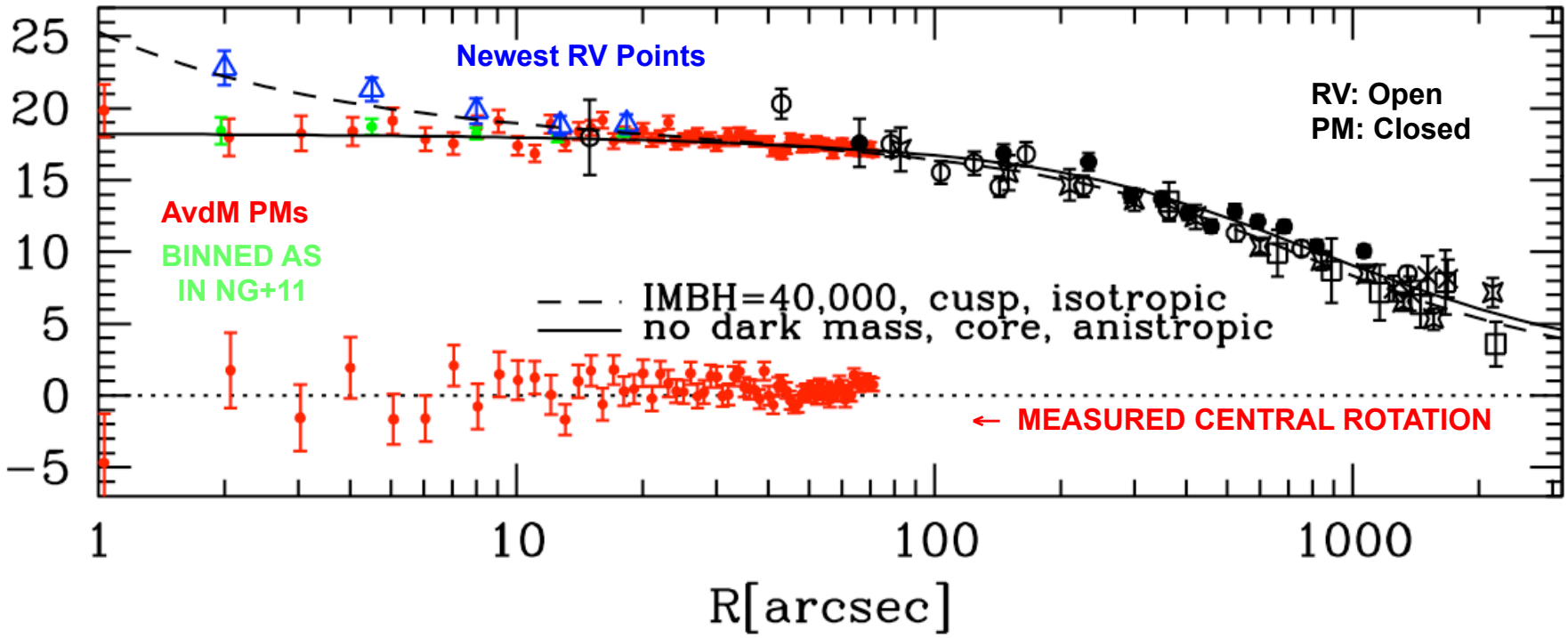
ω Centauri

Huge IMBH, or maybe none at all?

Major Point of Disagreement: Data

- σ_V(R) Profile
- Fast-Moving Stars

σ_V (km/s)

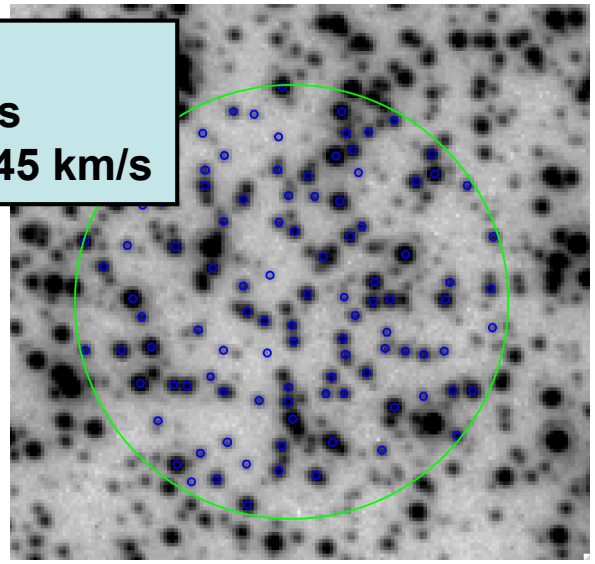


(relative to new NG+11 Kinematic Cen)

ω Centauri

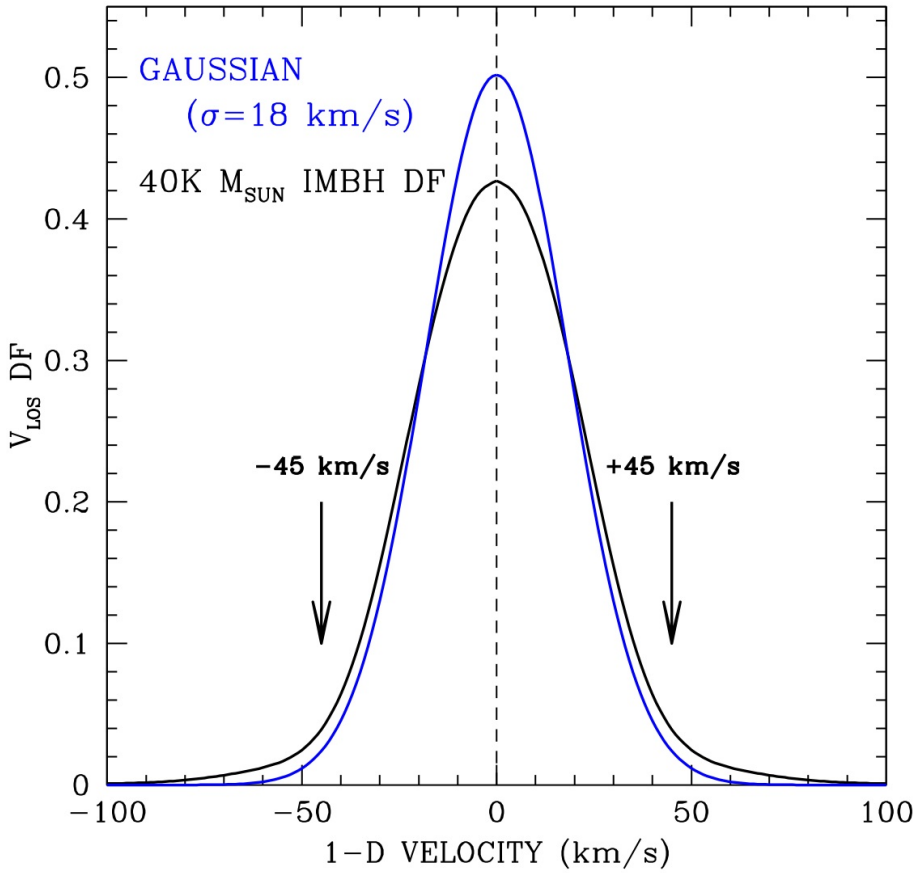
Huge IMBH, or maybe none at all?

109 Stars within 3″
→ 218 1-D velocities
→ No stars with v>45 km/s



Major Point of Disagreement: Data

- σ_V(R) Profile
- **Fast-Moving Stars**



Model of DF

Eddington's equation: f(E)
with isotropy
with cusp
trial IMBHs

Model Predictions:

IMBH	N_{PRED}	P(0)	σ_{PRED}
40,000 $M_\odot$	10.0		0.000035
23.1 km/s			
20,000 $M_\odot$	4.1	0.012	19.5 km/s
5,000 $M_\odot$	0.9	0.392	16.6 km/s

ω Centauri

Huge IMBH, or maybe none at all?

How to Resolve the Controversy?

- **Ideal: compare star-by-star**
  - → Good also for 3-D motions; Schwartzchild modeling
  - → Currently the star-by-star RVs only for giants/outside
- **Validate the motions**
  - → Multiple Independent measurements
- **Validate the models:**
  - → Centers (does the spatial center matter?)
  - → Spatial Profile
  - → Isotropy

  → We have made public all our catalogs.

- **N-Body contributions**
  - → non-equilibrium issues?
    - Dark remnants?
    - Wandering IMBH?
    - Mass Segregation (Pasquato et al. 2009)
- **Other data:**
  - → X-ray: nothing (Henke, personal comm.)
  - → Radio: Lu+ 2011
    - Tantalizing 2.5-σ radio detection at centers of both ω Cen & 47 Tuc
    - Upper limit of 1000 - 5000 $M_{\odot}$

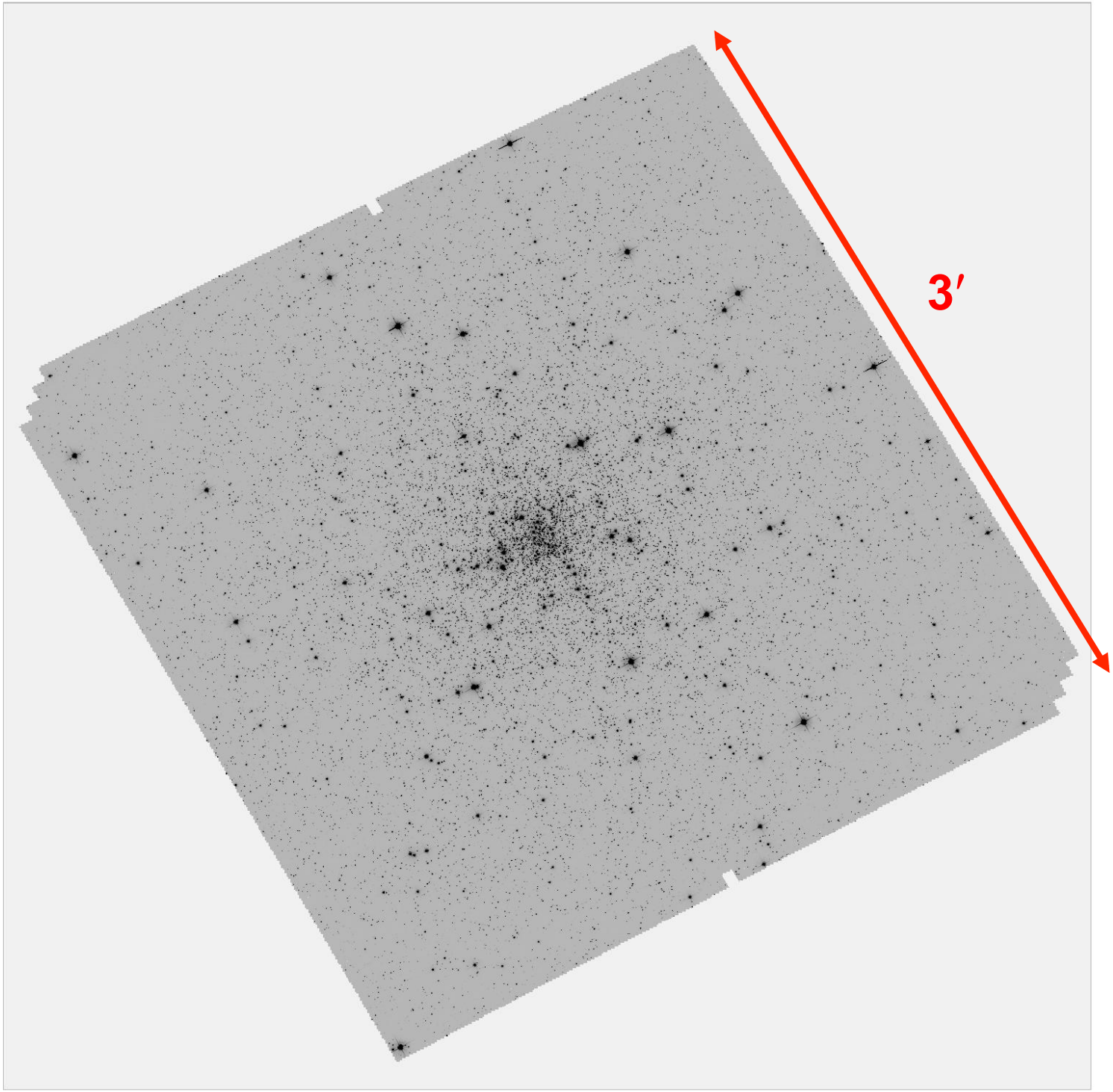
Preliminary Results
Other Clusters

Cluster	Dist (kpc)	σ_{RV} (km/s)	σ_{PM} (mas/yr)	Mass ($M_\odot$)
NGC6752	4	4.9	0.25	2×10^5
NGC6341	8.3	6.0	0.15	3×10^5
NGC2808	9.6	13.4	0.27	9×10^5

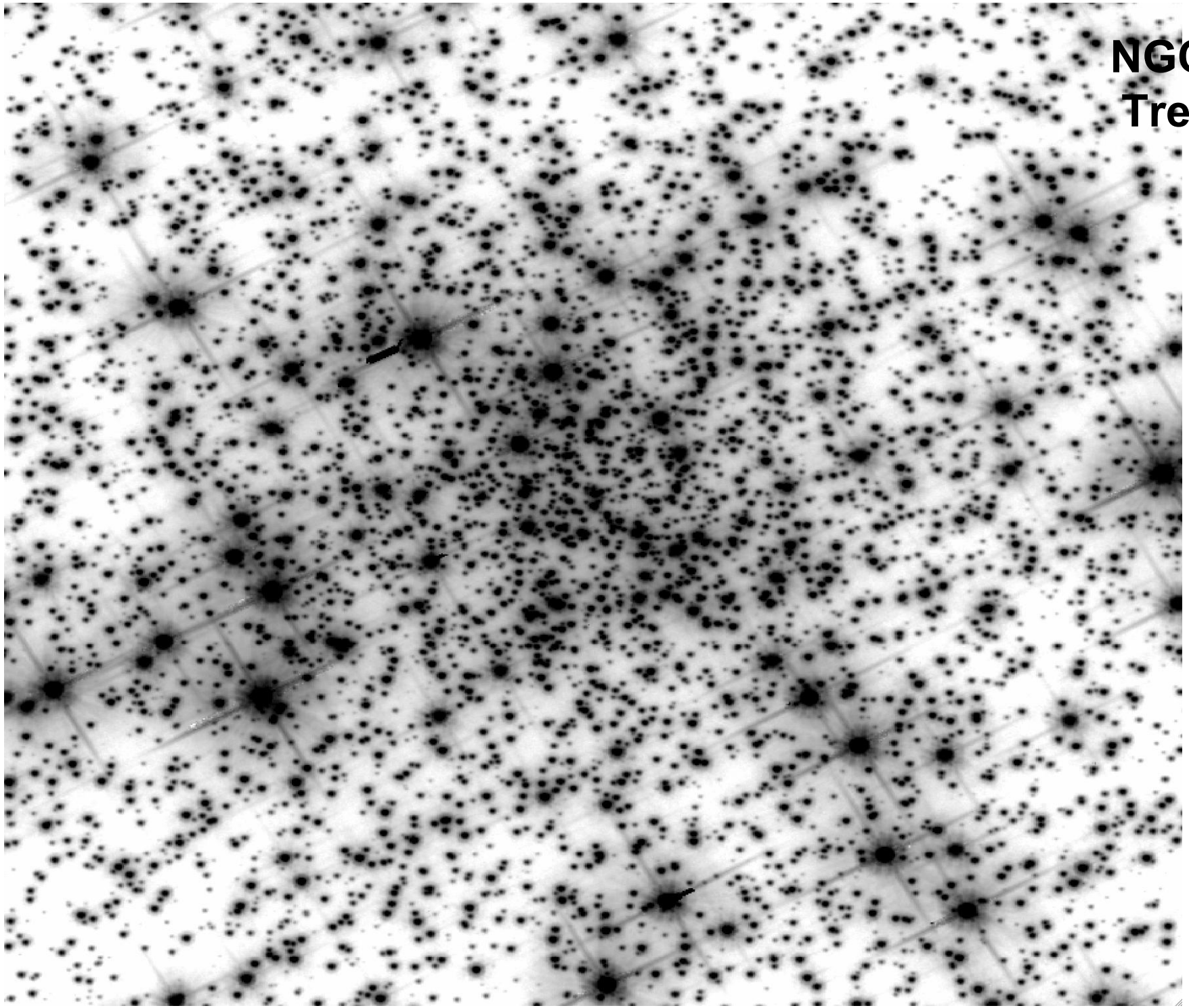
Data Overview

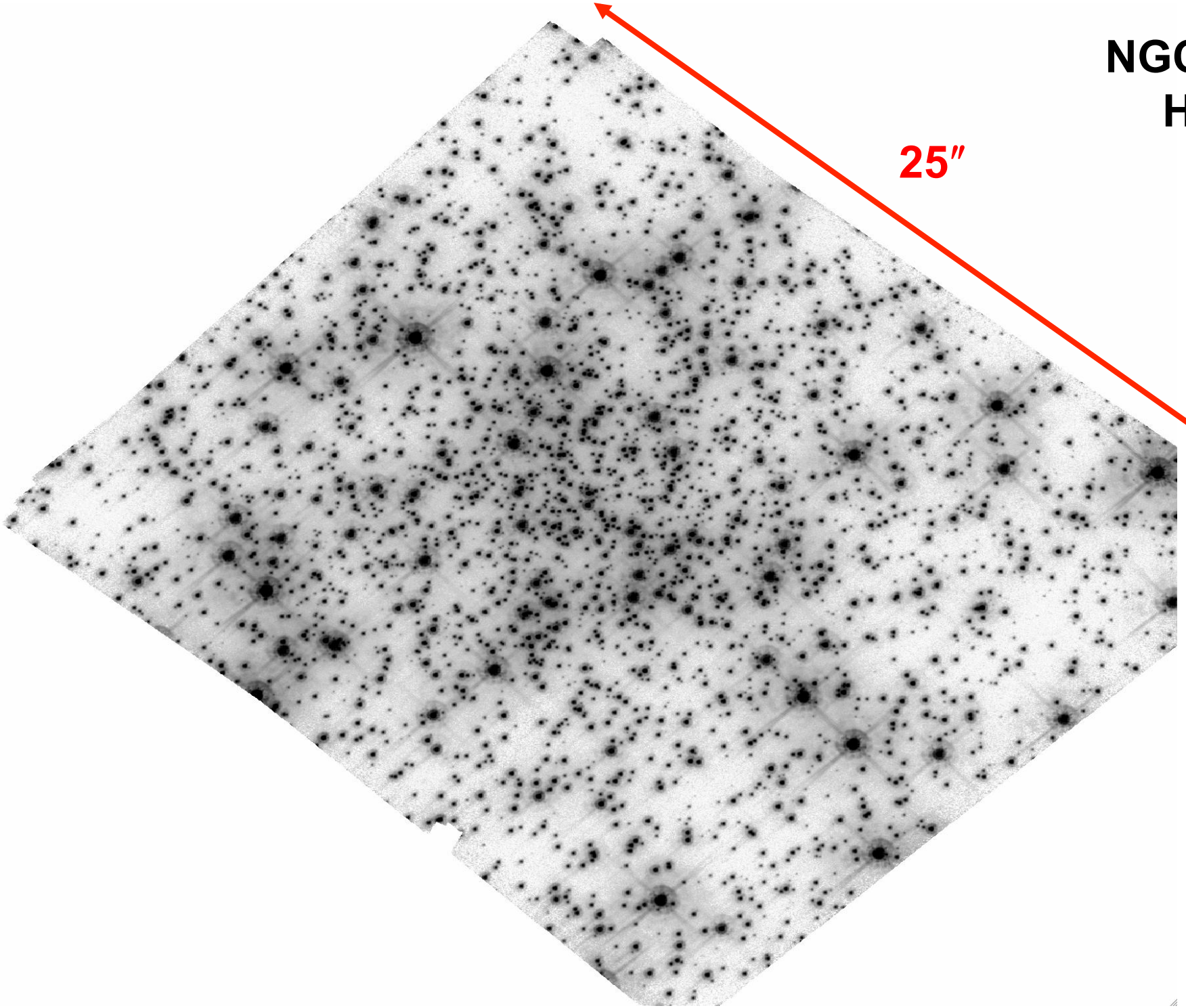
- **Profile/center: WFC: 3′×3′**
  - 2006 4×F606W, 4×F814W (Ata's Treasury data)
- **Core motions: HRC/UVIS subarray: 30″×30″**
  - 2005 12×F435W HRC images of core
  - 2007 12×F435W HRC images of core
  - 2010 8×F438W WFC3/UVIS images of core
- **Outer motions: WFC/UVIS data: 3′×3′**
  - 2004-2011 wide-field observations in archive/GO

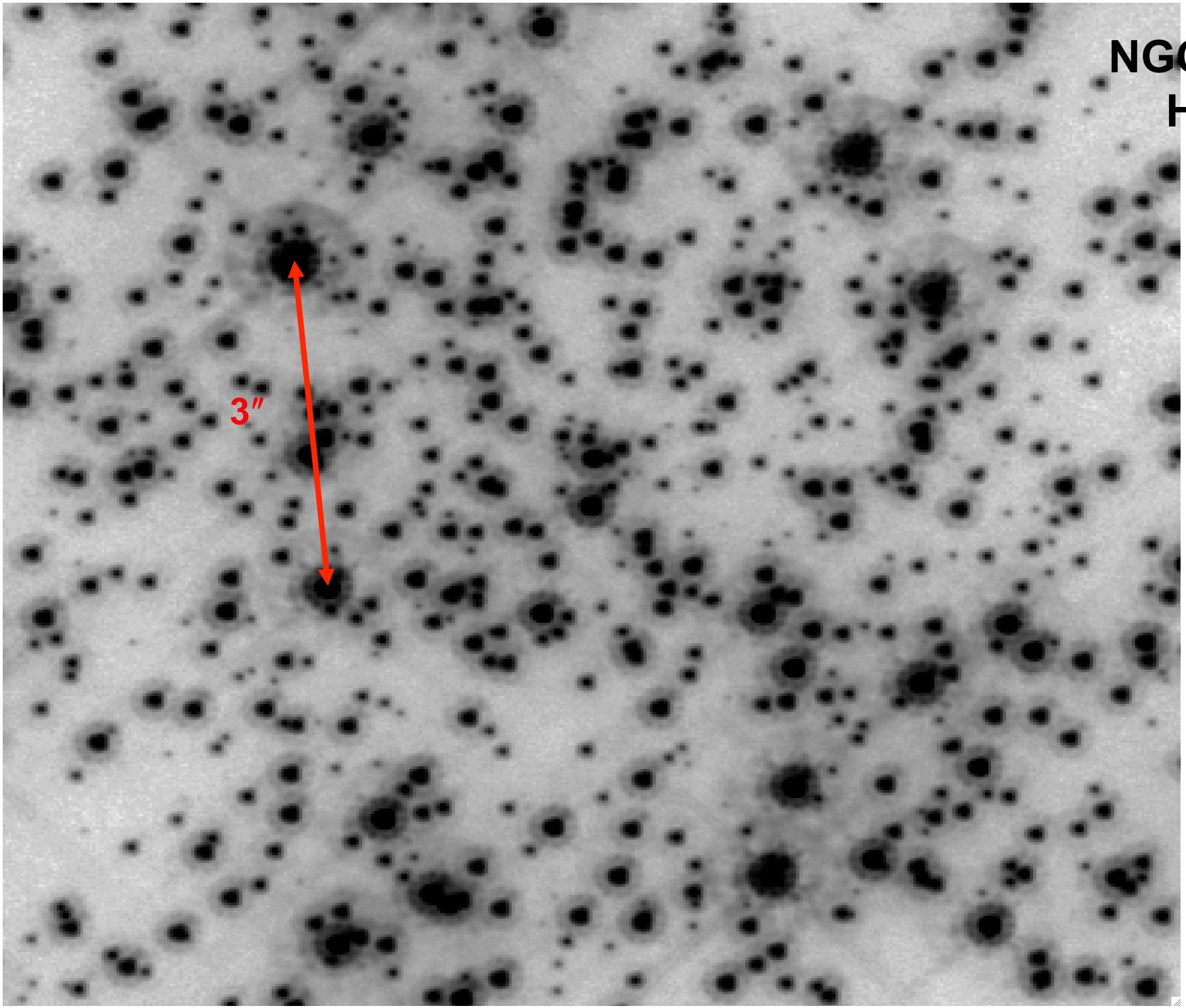
OPTIMIZED FOR ASTROMETRY!



NGC 6752
Treasury

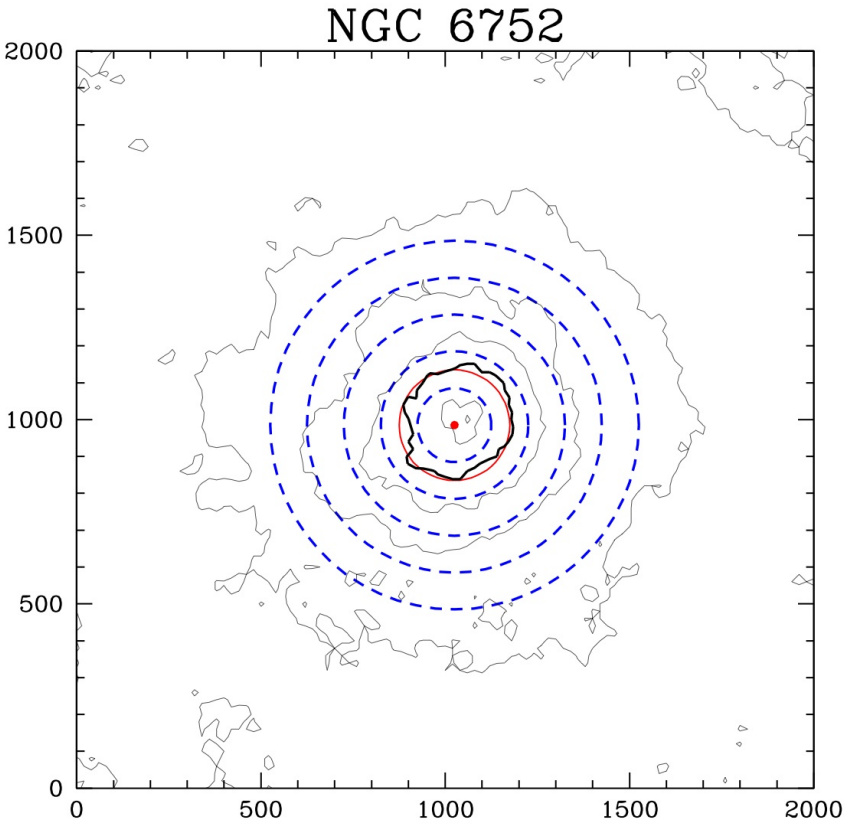

NGC 6752
Treasury

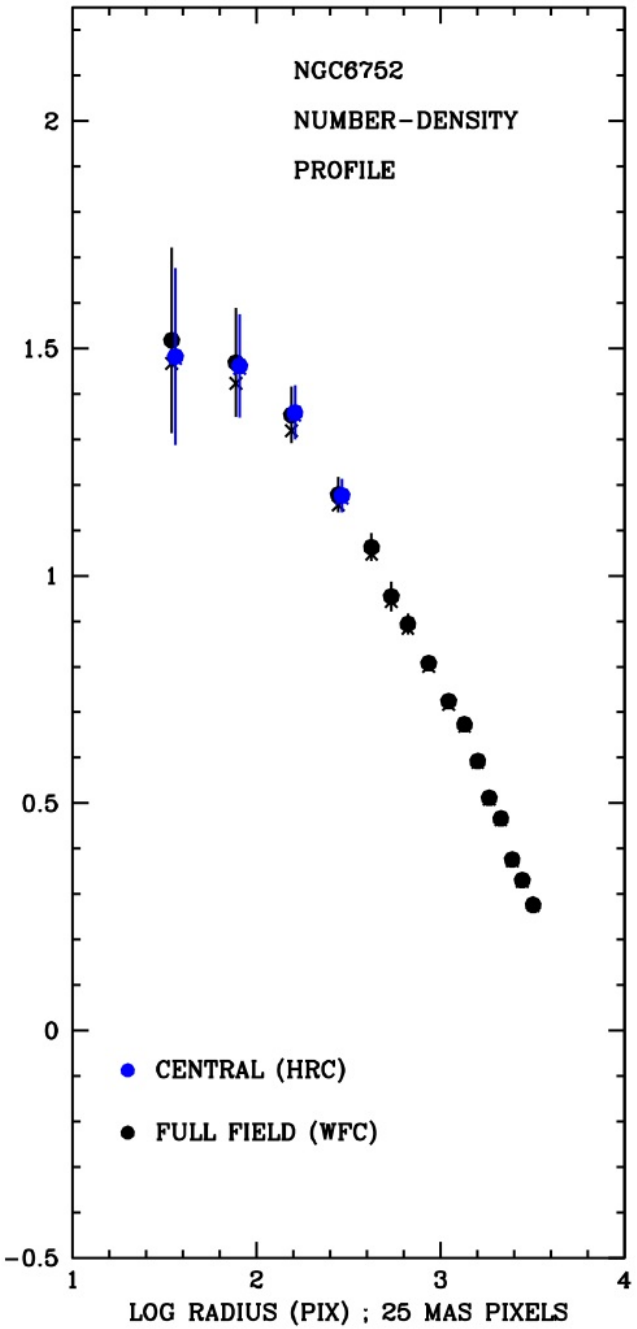

NGC 6752
HRC
25″


NGC 6752
HRC
3″

Center and NDP

- **Contours**
  - Goldsbury et al. 2010
  - HRC field too small
  - Use WFC Treasury data



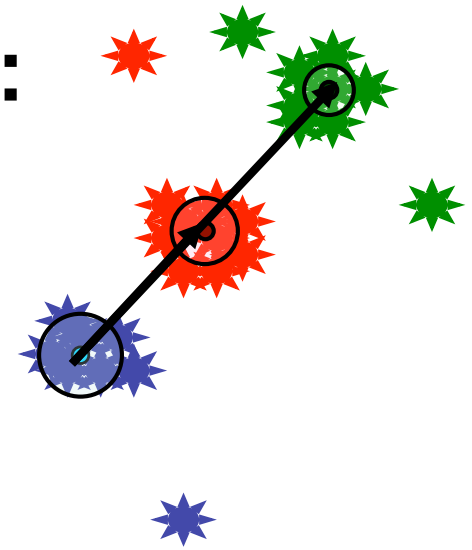


THE FULL DATA SET

For each star:

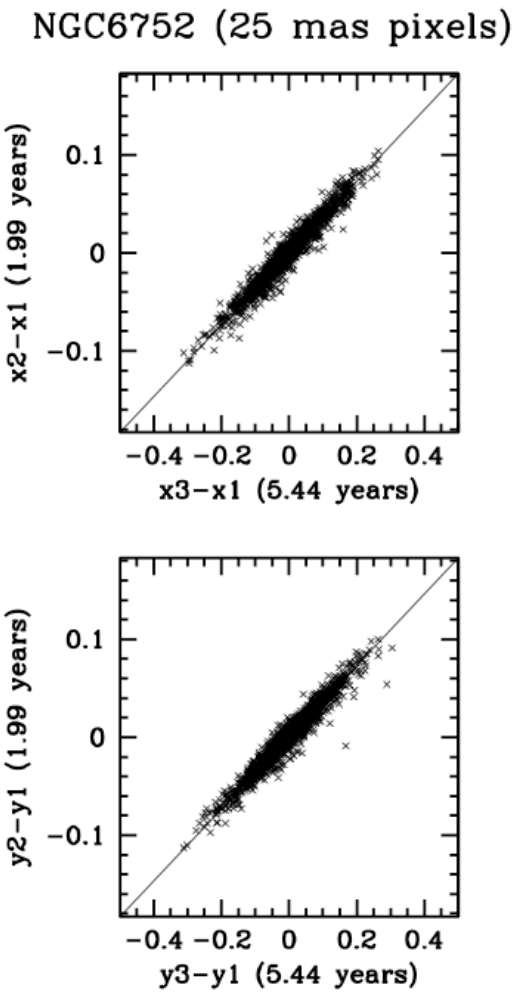
– **RAW:**

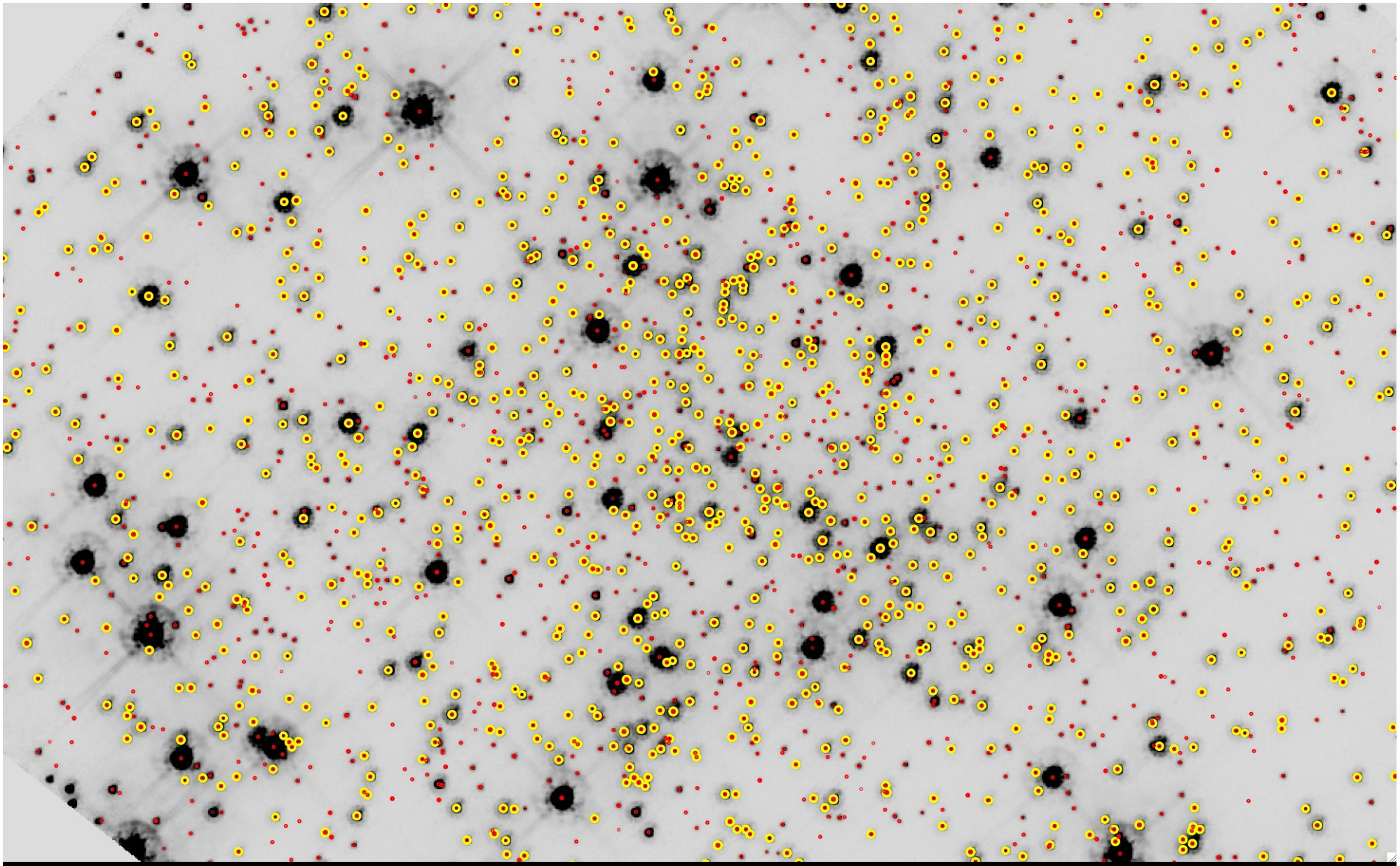
- x_1, y_1, m_1
- x_2, y_2, m_2
- x_3, y_3, m_3,
- m_V



– **DISTILLED:**

- x_{BAR}, y_{BAR} (pixels)
- D_{CEN} (arcsec)
- μ_X, μ_Y (mas/yr)
- σ_μ (mas/yr)
- χ (e_2 agreement)
- m_B-m_V , m_B

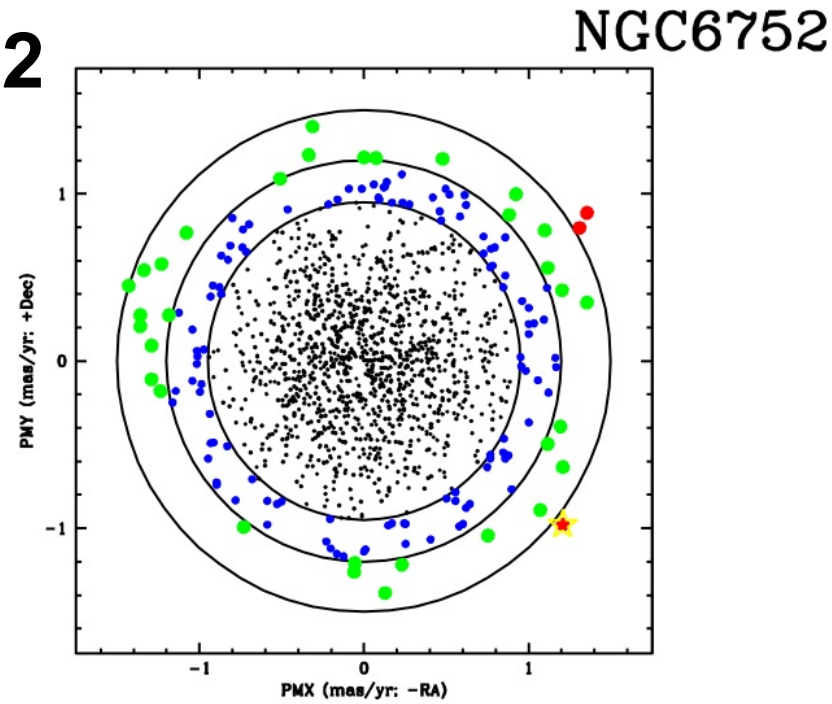




NGC 6752 STARS

NGC6752 PMs

VECTOR-POINT DIAGRAM:

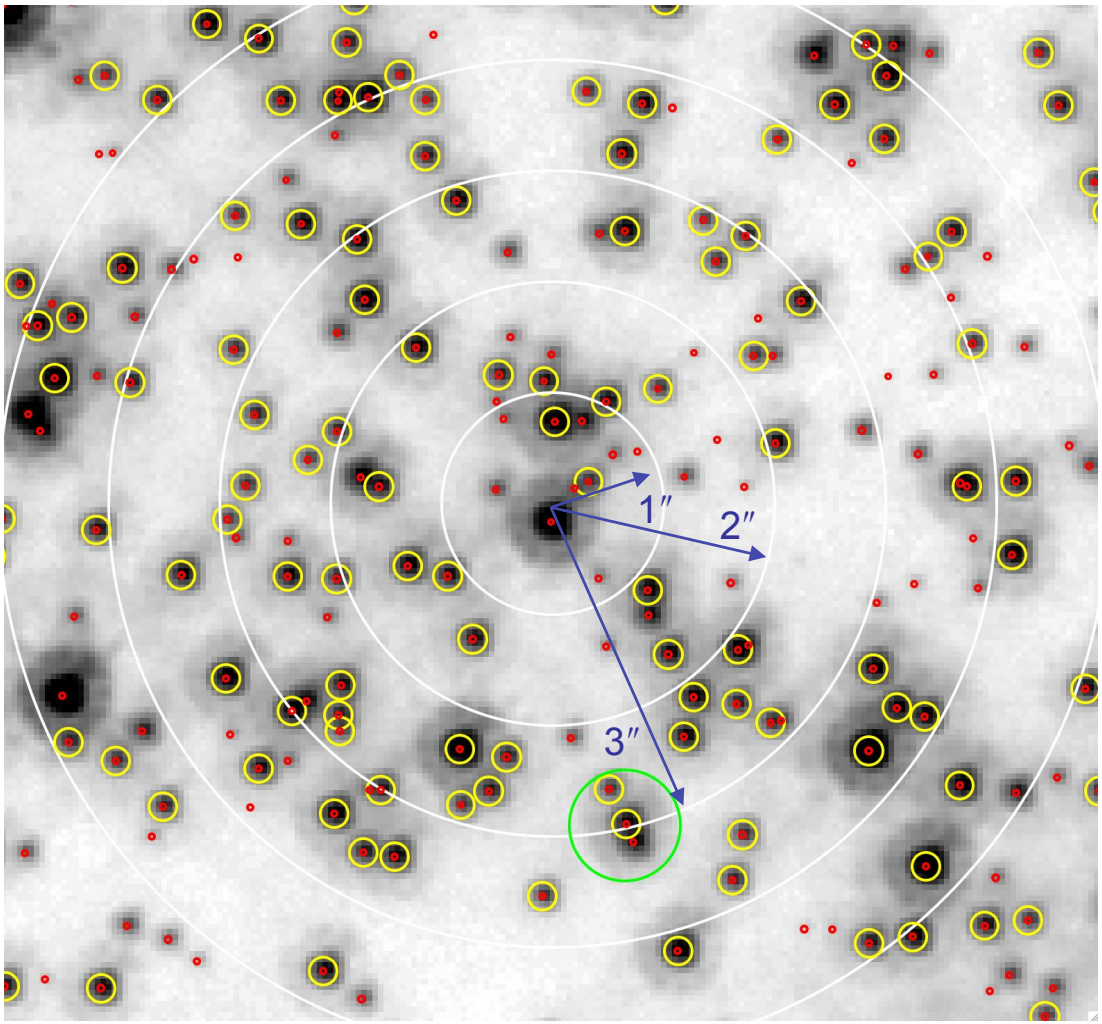


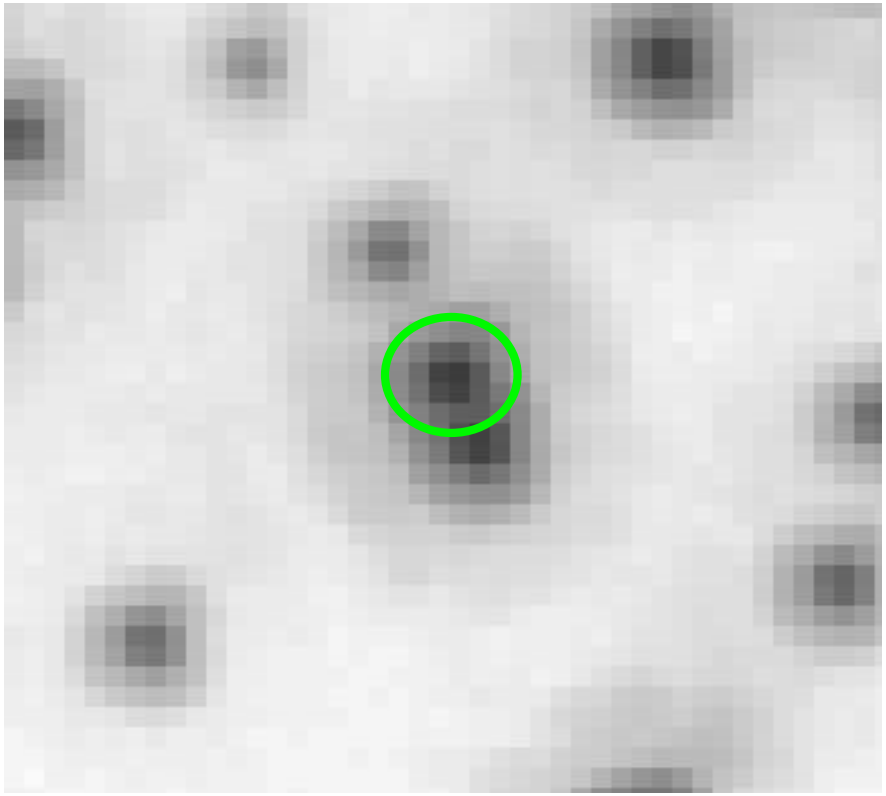
2-D to 3-D …

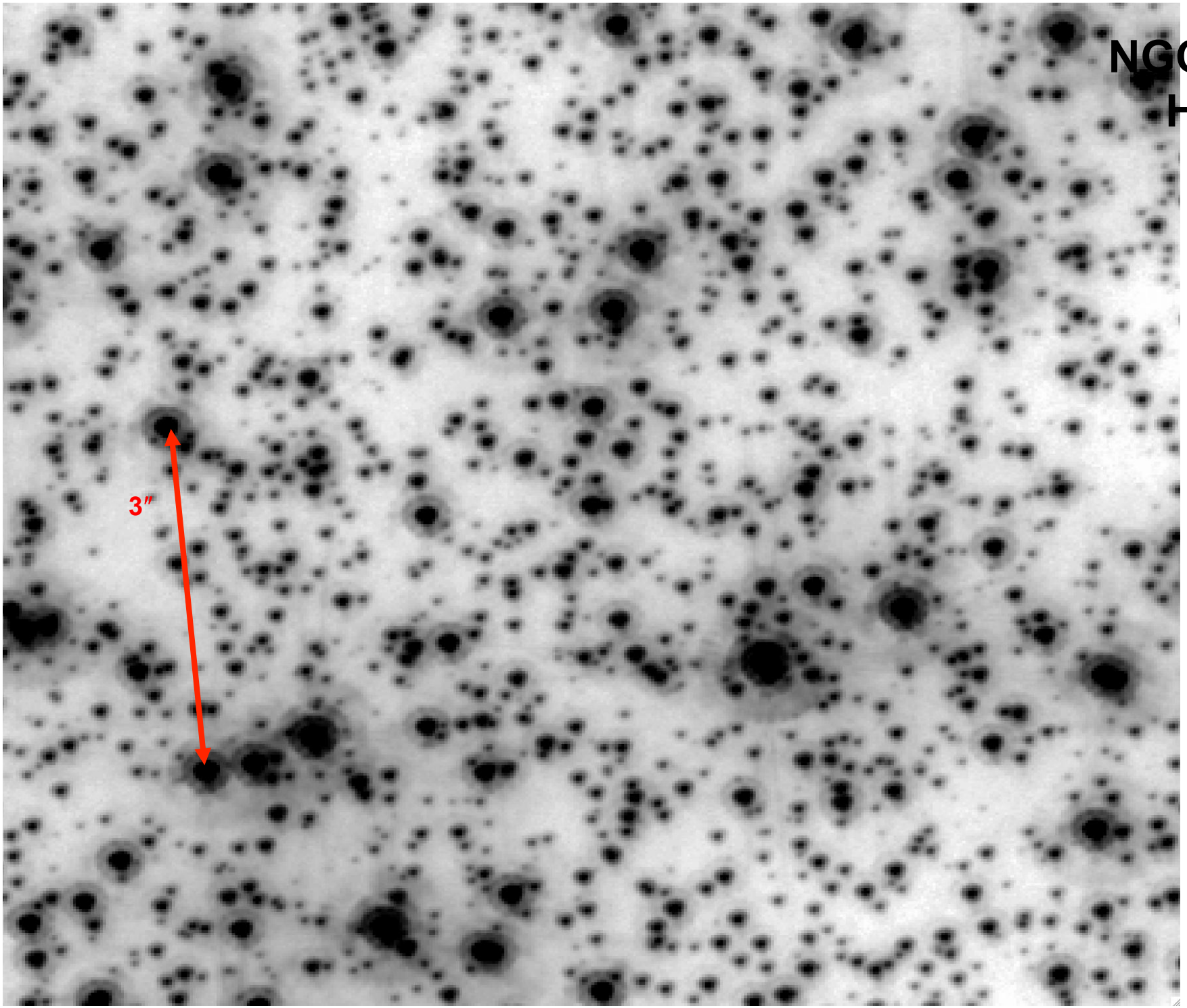
Which stars can be physically closest to the center?

→ could be any star within 2″

Need to carefully evaluate quality and likelihoods for small-number statistics of fast stars…

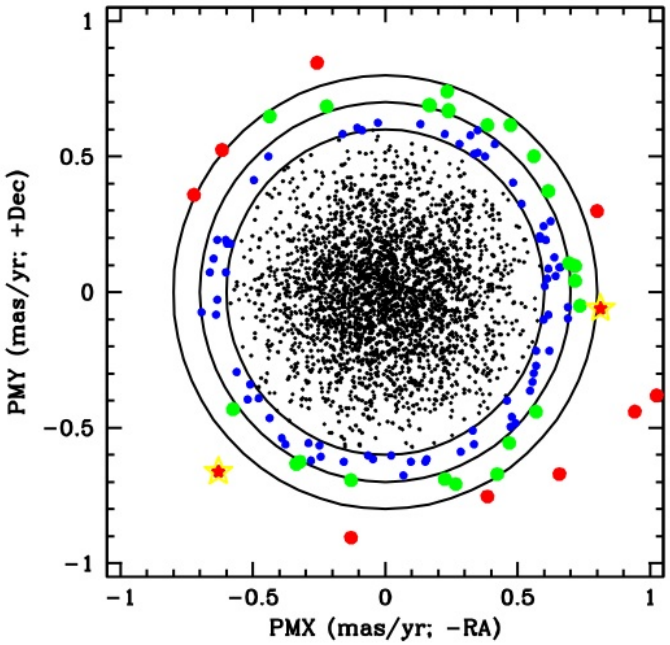


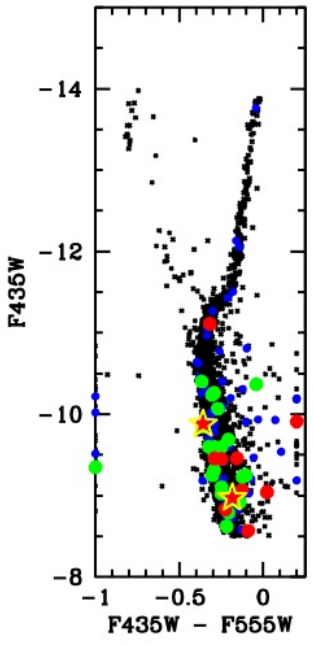


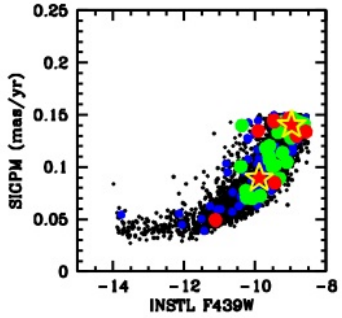

NGC 6341
HRC
3″

NGC6341

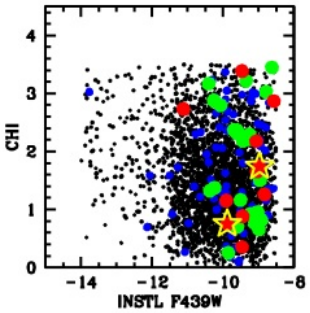
VECTOR-POINT DIAGRAM:





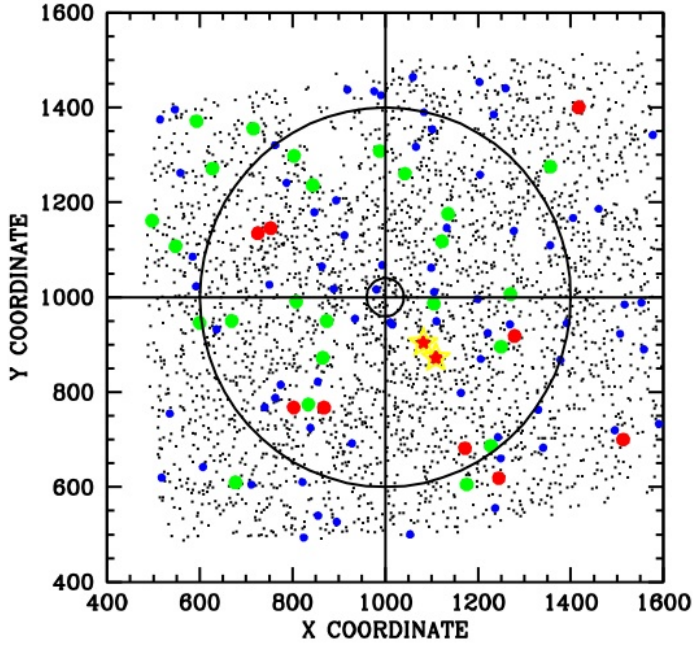


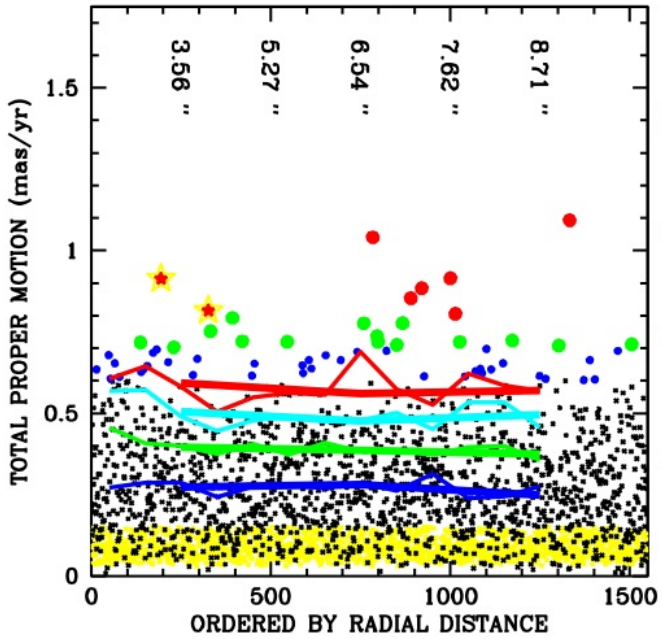
ERROR-VS-MAGNITUDE



AGREEMENT WITH MIDDLE EPOCH

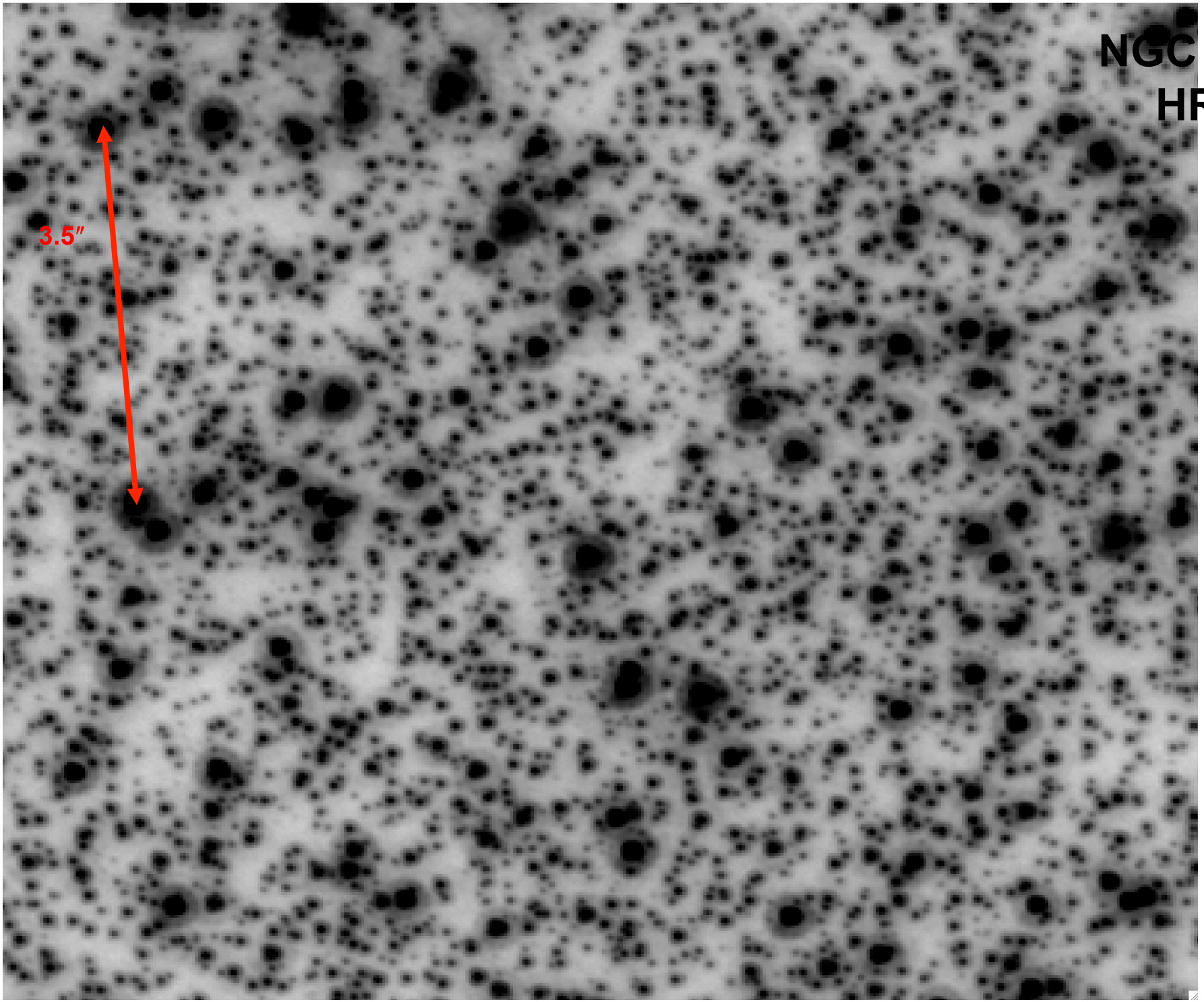
PHYSICAL LOCATION:

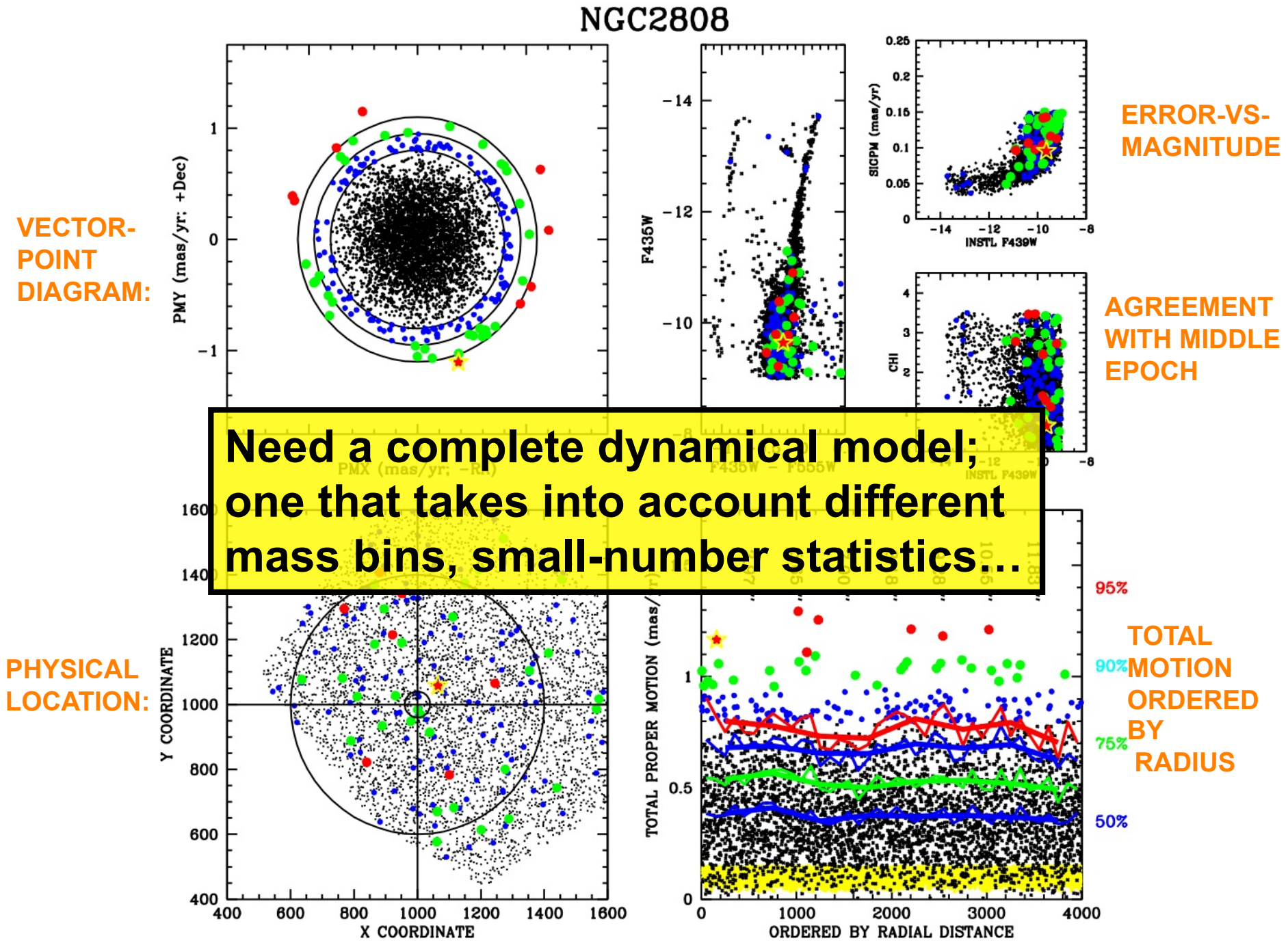




95%
90%
75%
50%

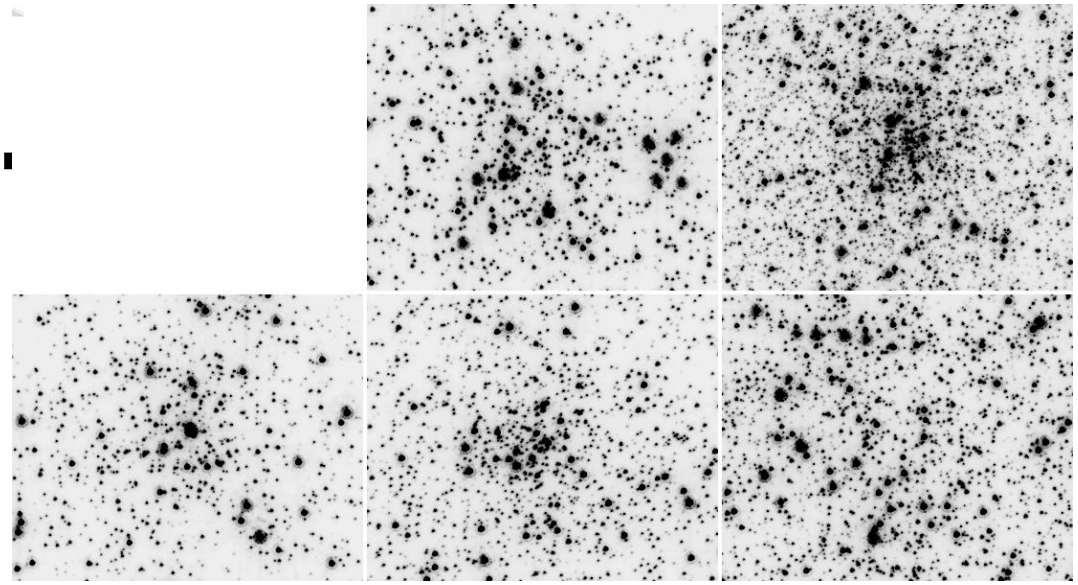
TOTAL MOTION ORDERED BY RADIUS


NGC 2808
HRC
3.5″

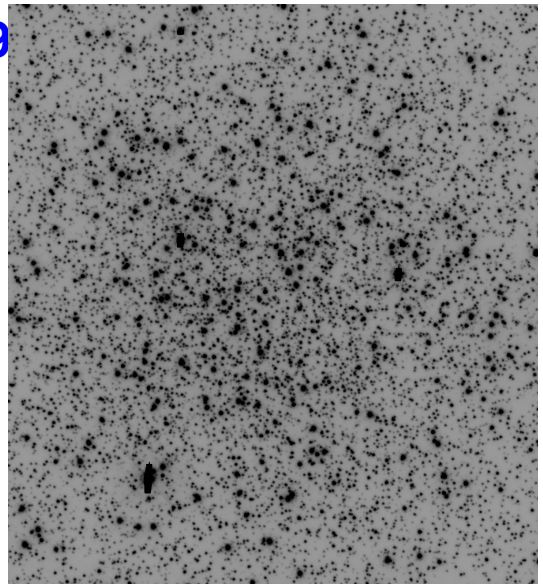

NGC2808
VECTOR-POINT DIAGRAM:
PMY (mas/yr; +Dec)
PMX (mas/yr; -RA)
F435W
F435W − F555W
SIGPM (mas/yr)
INSTL F439W
CHI
ERROR-VS-MAGNITUDE
AGREEMENT WITH MIDDLE EPOCH
Need a complete dynamical model; one that takes into account different mass bins, small-number statistics…
PHYSICAL LOCATION:
Y COORDINATE
X COORDINATE
TOTAL PROPER MOTION (mas/
ORDERED BY RADIAL DISTANCE
95%
90%
75%
50%
TOTAL MOTION ORDERED BY RADIUS

Coming soon..

- ω Cen
  - More stars, deeper & brighter!



- **Other clusters**
  - **IMBH studies**:
    - **NGC 362, NGC6624, NGC6681 NGC7078, NGC7099**
      HRC + WFPC2 + …; all data in hand for… (PI-Chandar)
      (collaborators: Ivan King, Roeland van der Marel, Holland Ford, Laura Ferrarese)
    - **NGC6266** WFC + UVIS… PI-Chaname
    - **M54…** Cycle 18 in September 2011 ; PI-vdMarel
- **Modeling improvements**
  - Include mass in Jeans models


NGC 6266

A very good time for cluster studies!!


Ground-based → ACS → WFC3/UVIS → PMs!

GO-11677
PI-Richer

47Tuc Outer
Calibn Field

ARCHIVE
2002-2007

GO DATA
2010
121 orbits