Proper Motions at the Center of ω Cen

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Globular cluster or Dwarf Spheroidal?

Uses of Proper Motions in Globular Clusters

- **Things we can measure:**
  - Cluster-field separation
  - Fundamental distances
  - Anisotropy (directly)
  - Velocity distribution function (directly)
  - Orbits in Galaxy
  - Central IMBH

- **Here:** (1) measure motions
  (2) fit a dynamical model

IMBHs in Globular Clusters

- **Several ways to find (PMs or RVs)**
  - Fast moving star in orbit (smoking gun)
  - Rise in velocities at center
    - Either in the dispersion or in non-Gaussian wings
- **Several ways to *not* find**
  - Not enough stars to sample its environs
  - Nearby stars all dark, ejecting binaries
- **Easiest places to look:**
  - Clusters with cusps & slow velocities
    - Paper by Drukier & Bailyn 2003
  - Omega Cen is *not* the easiest place to look
    - Yet…

IMBH History

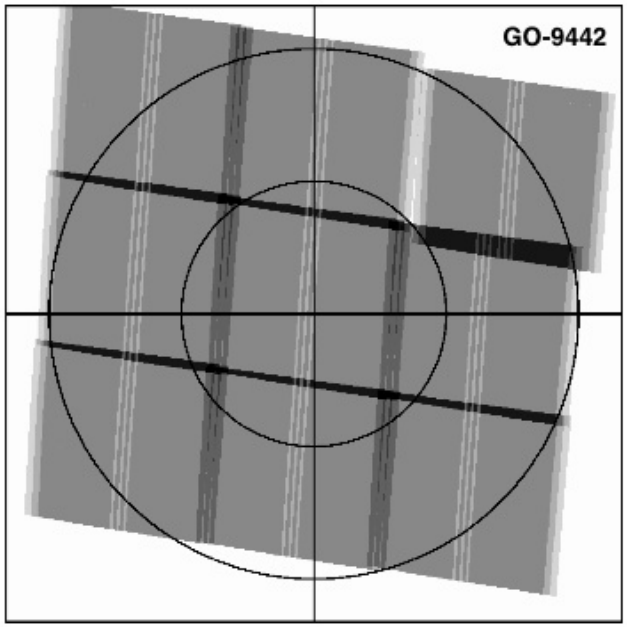
- **M – σ relation predicts 1,000 - 10,000 M_{SUN} BH**
- **Detections/limits in the literature**
  - M15: back and forth; currently not required…
  - 47 Tuc: upper limit of 1500 M_{SUN} (McLaughlin et al 2006)
  - G1?
- **Recent interesting result in ω Cen**
  - Noyola, Gebhardt & Bergmann 2008 (NGB08)
    - Detected a brightness cusp at center in ACS images
    - Used an IFU at Gemini to measure velocity dispersion

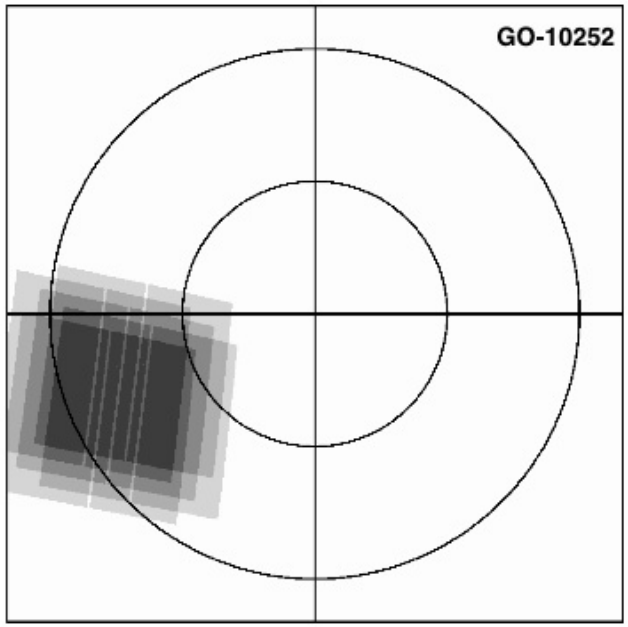
      They found:

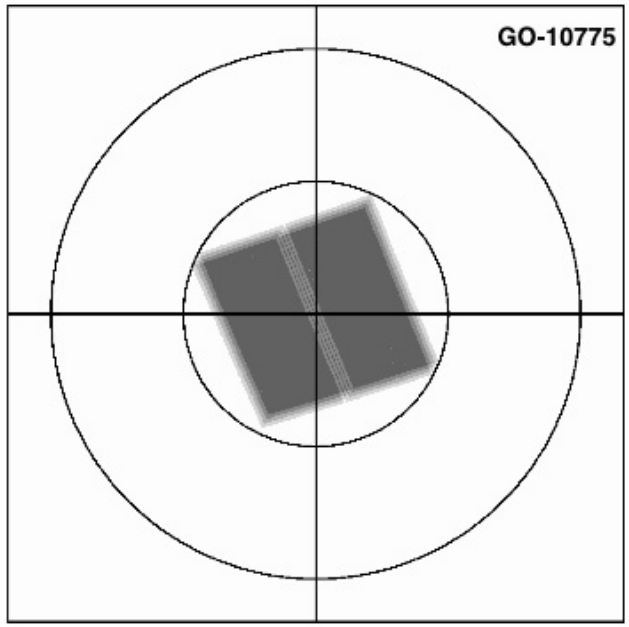
      σ_{RV} = 23.0 ± 2.0 km/s at center, and

      σ_{RV} = 18.6 ± 1.6 km/s at 14″ (in-line with overall σ_{RV} trend)
    - Concluded that this could be explained by a 40,000 M_{SUN} IMBH
  - This dispersion increase should be detectable in proper motions…

The ACS Data







2002.49

GO-9442
PI-Cool
3 × F435W
4 × F658N
3 × F625W

2004.95

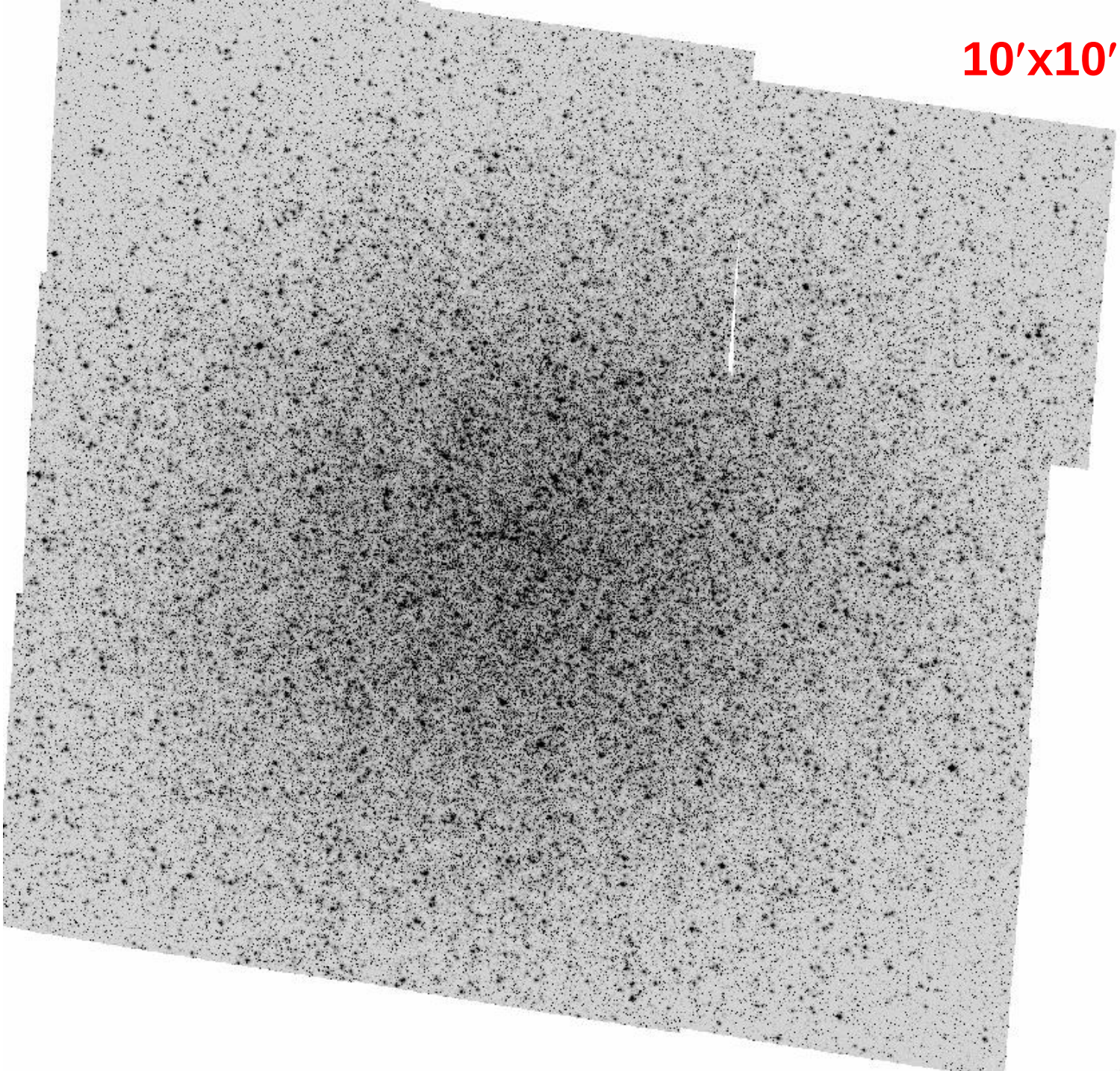
GO-10252
PI-
Anderson
5 × F606W
5 × F814W

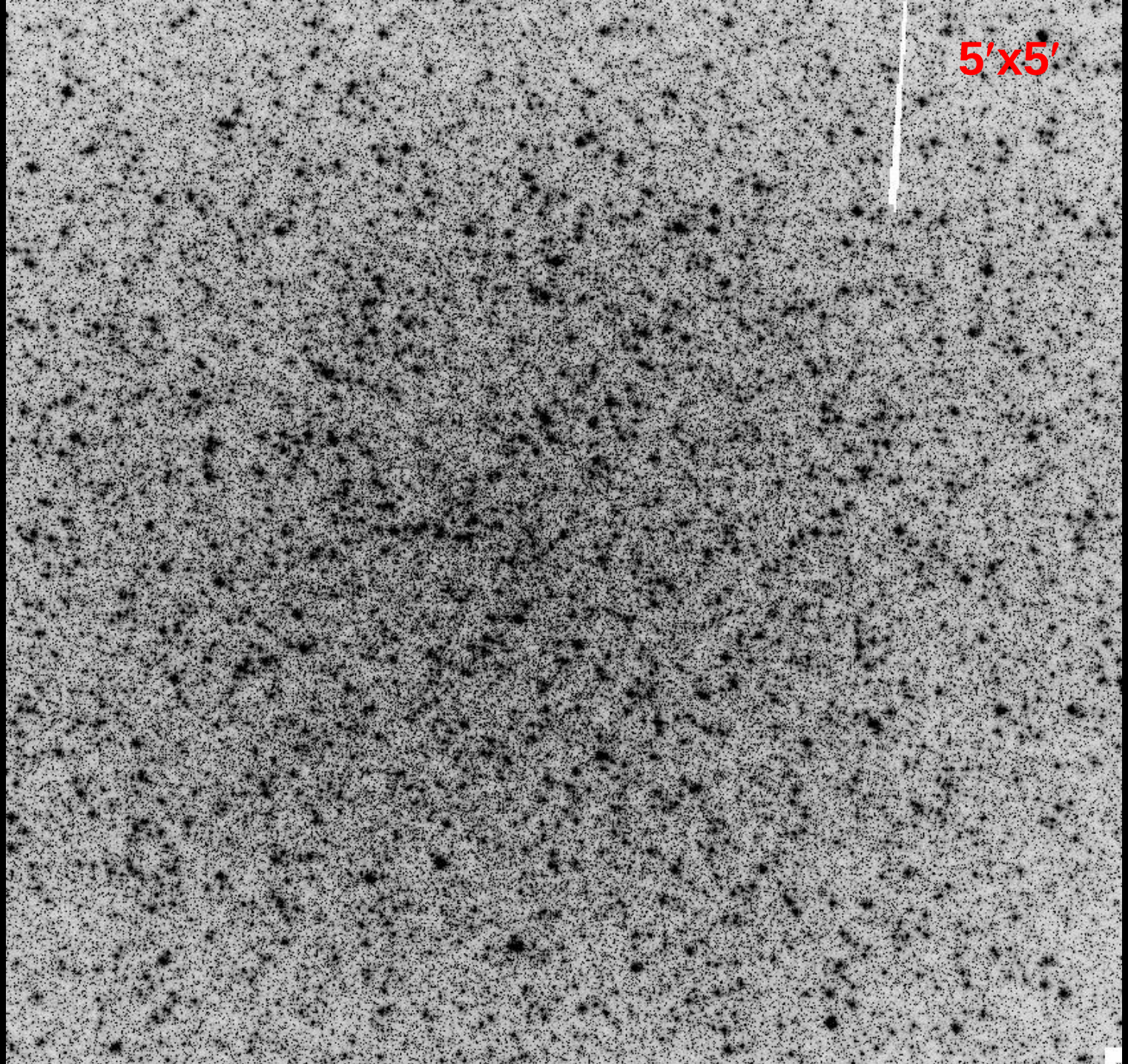
2006.56

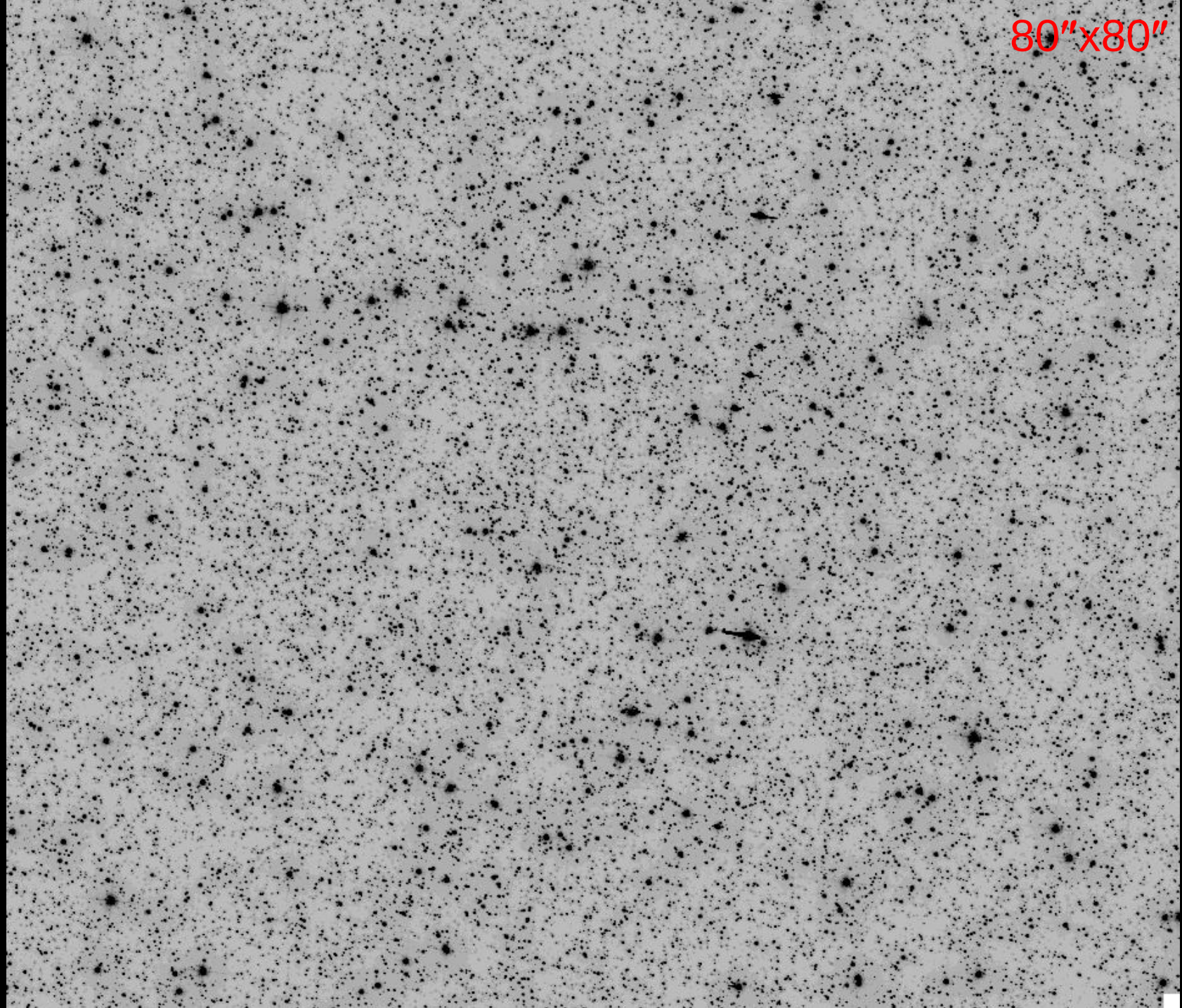
GO-10775
PI-Sarajedini
4 × F606W
4 × F814W

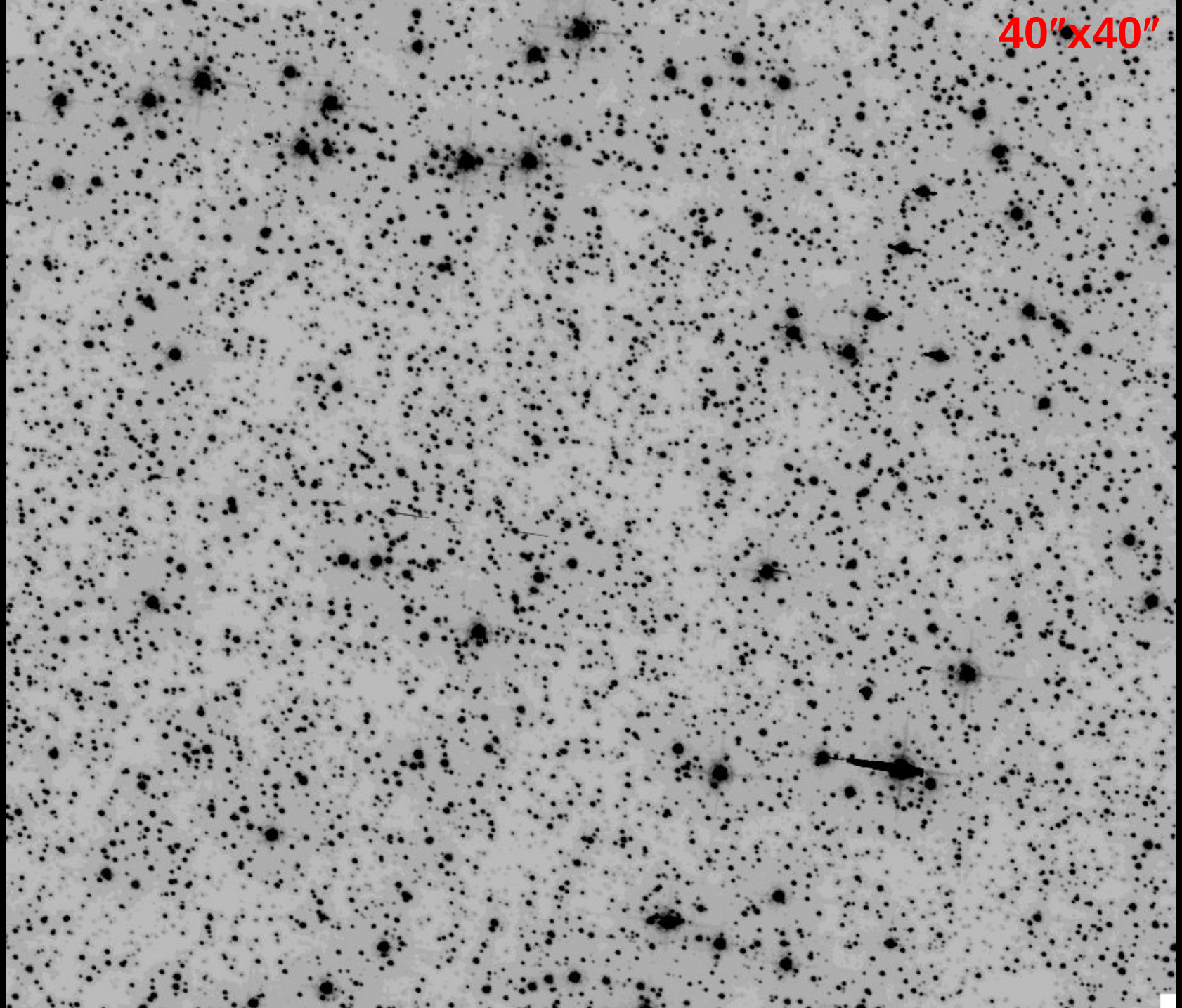
Set-up

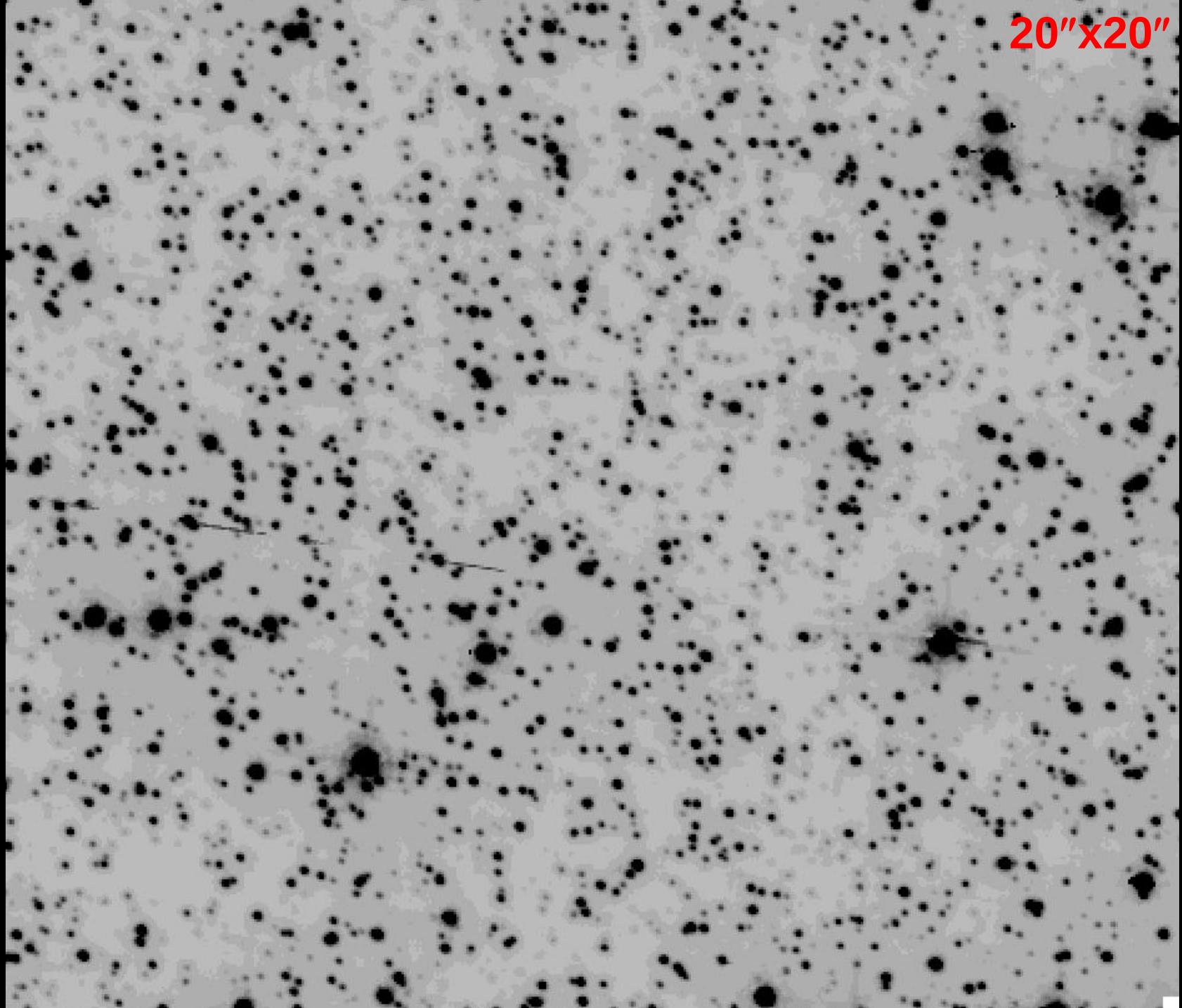
- Reference frame based on 3×3 mosaic
- Gorgeous 14000×14000-pixel image


10′x10′


5′x5′


80″x80″


40″x40″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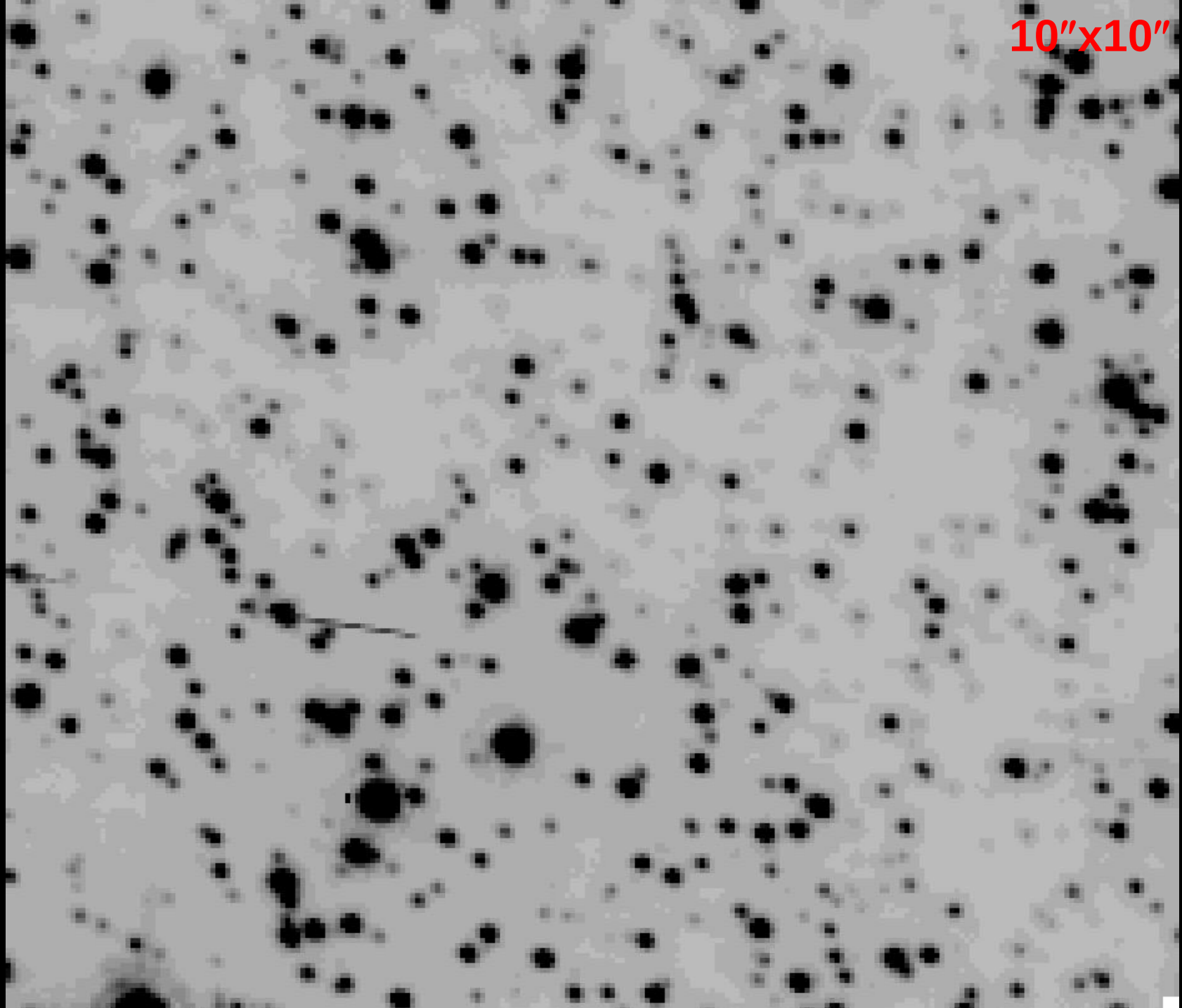
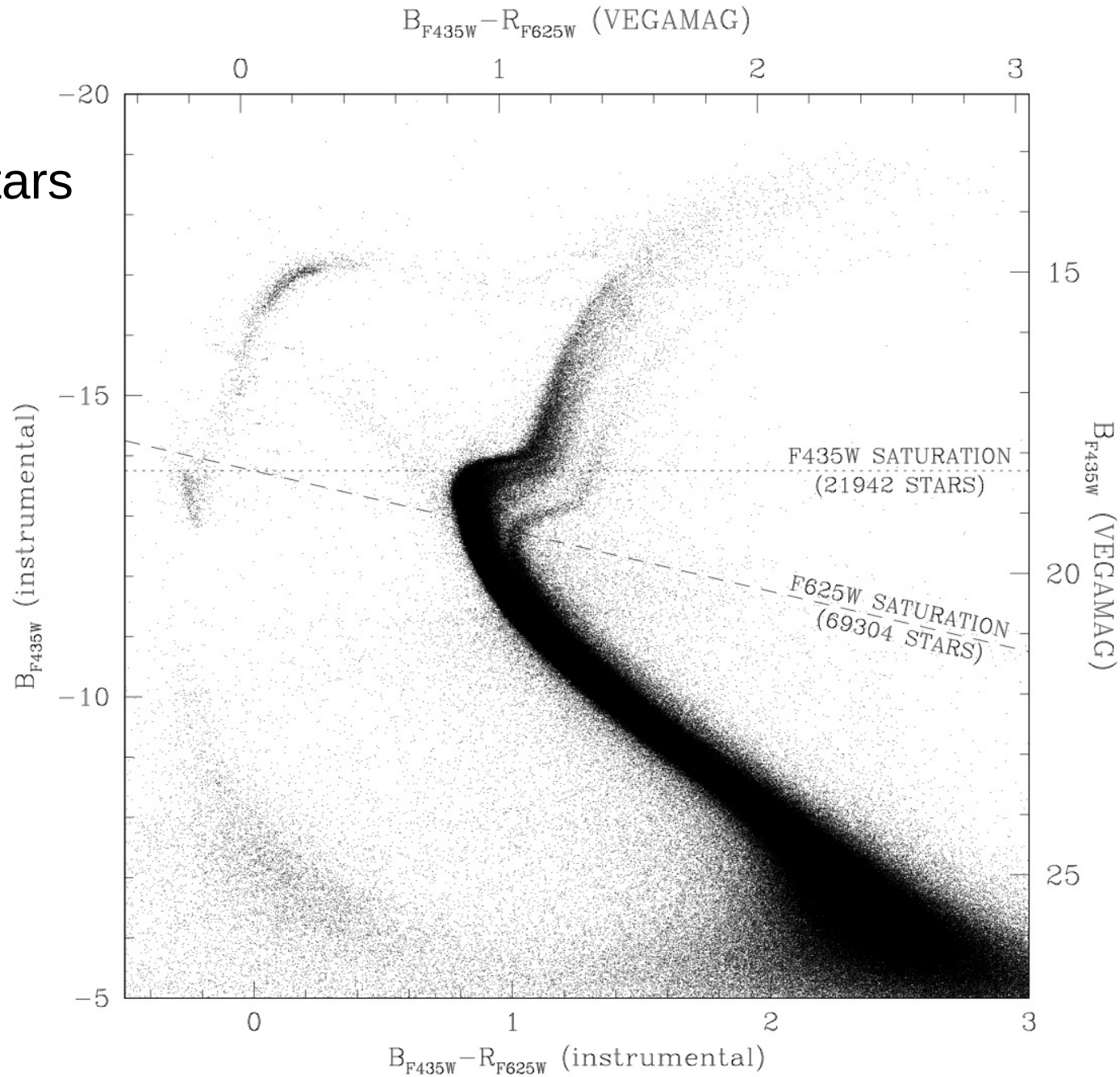

10″x10″

Reductions

- **Automated finding routine**
  - Master star list of 1,164,317 stars
  - Artificial-star run of 500,000 stars
    - 700 in central arcsecond
- **Proper motions**:
  - Measured unsaturated stars in each individual deep exposure
    - 10 in first epoch
    - 8 in second epoch
  - Correct for distortion
  - Carefully transform into reference frame
  - Combine by epoch
- **All data will be made public**

CMD

1,164,317 stars

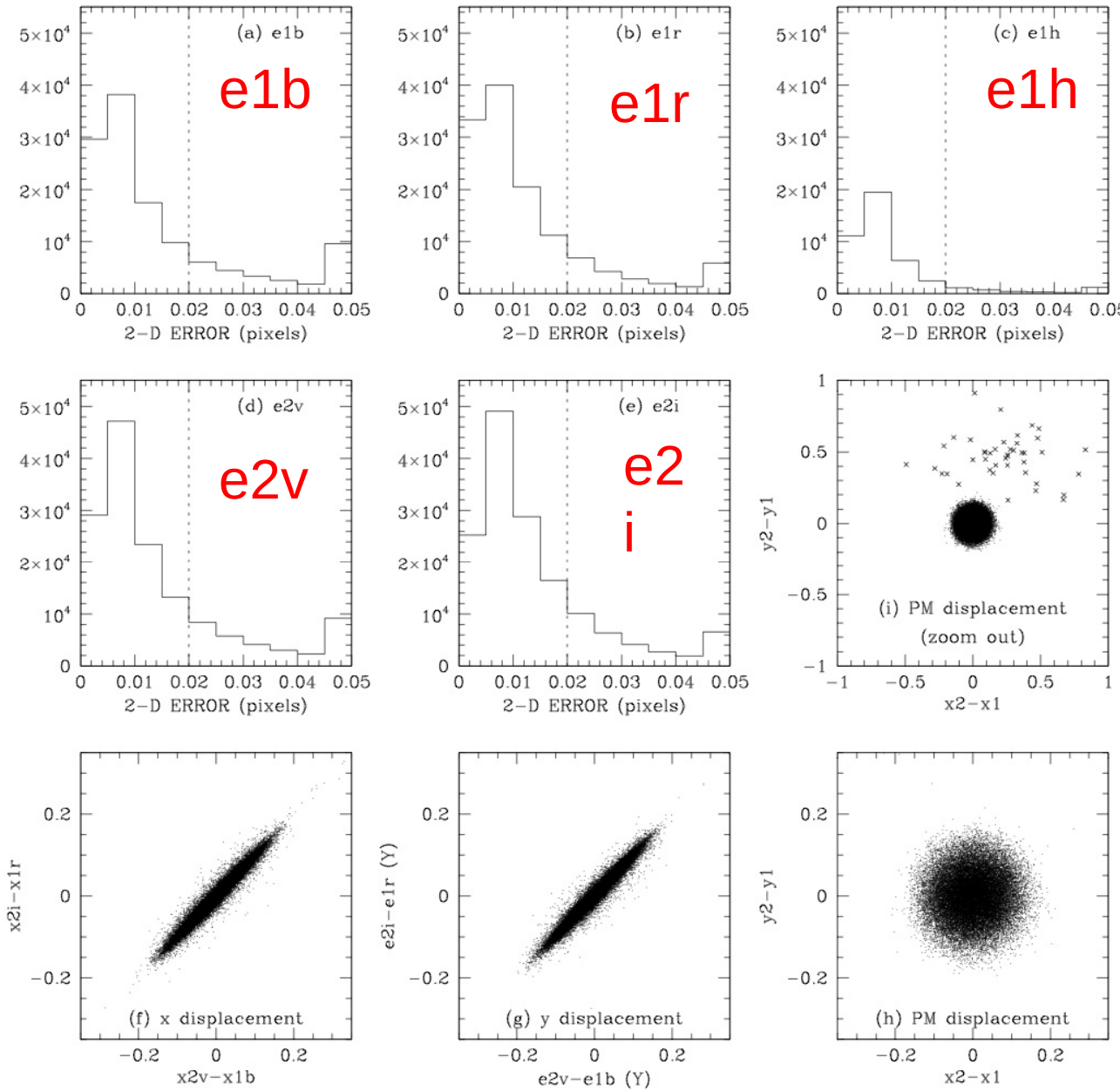


Proper motions

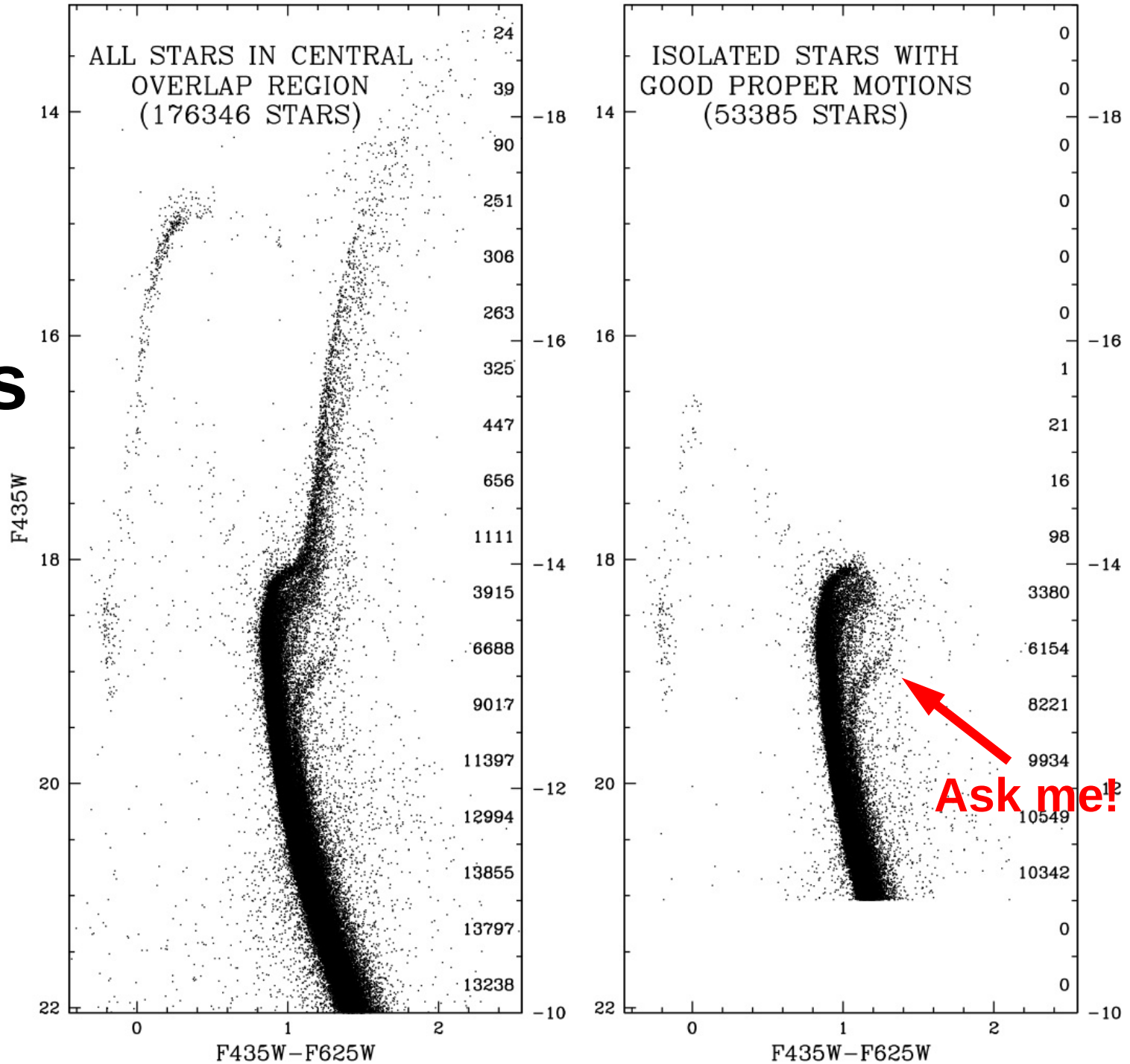
Require a consistent positions at each epoch

0.02 pix = 1 mas

An independent check…



Stars with Good Motions

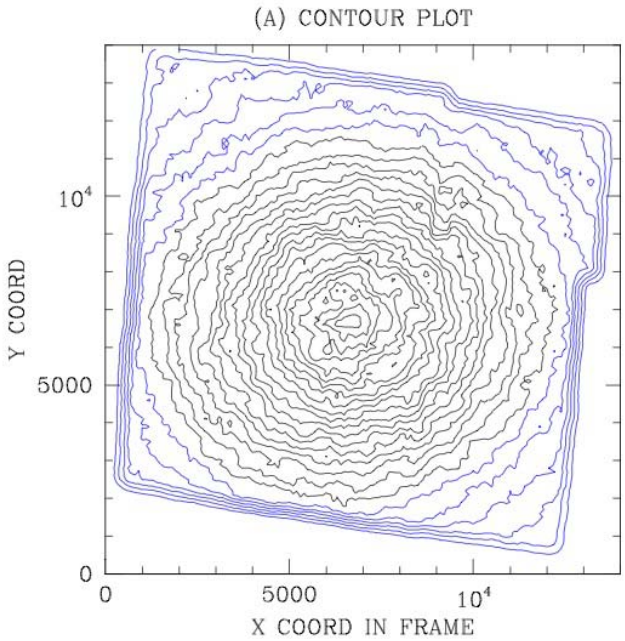


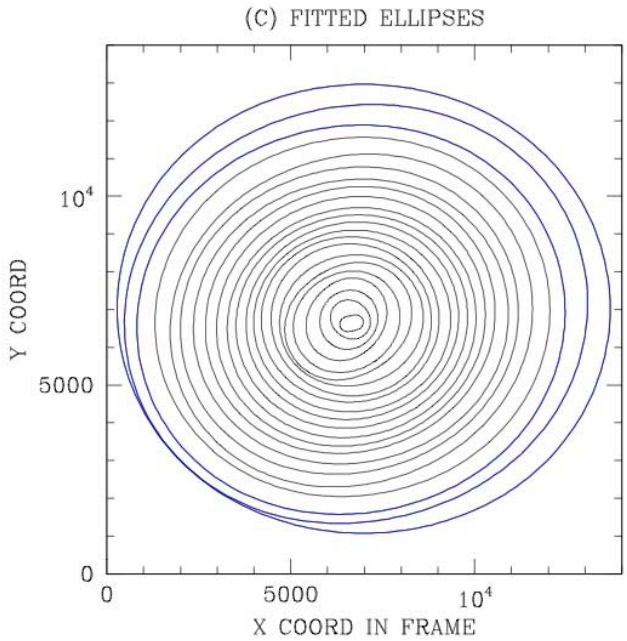
Finding the Center

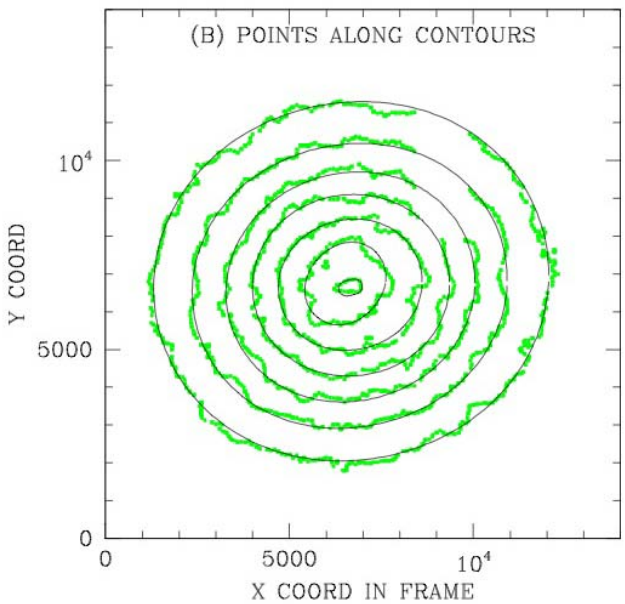
- Literature: no errors
- General: error ~ σ / $\sqrt{N}$
  - Need to go out to at least a core radius
  - For ω Cen, r_c = 2.5′ = 150″
    - Need ~22,500 stars to get σ_{CEN} to be 1″
    - Full coverage, no biases
- I will use three largely independent methods
  - Contours
  - Pie slices
  - Velocity dispersion

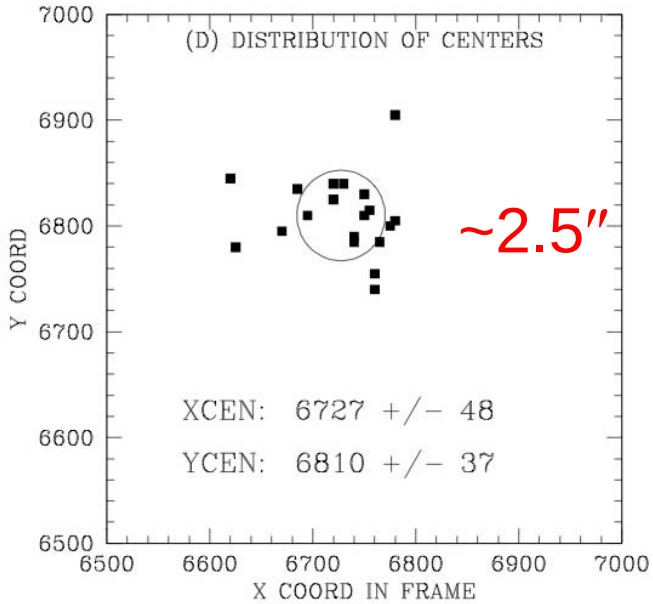
Method 1 Finding the center using contours

- 500×500 regions
- over 500,000 stars
- down to $m_{F435W} = -9$ (S/N ~ 40)



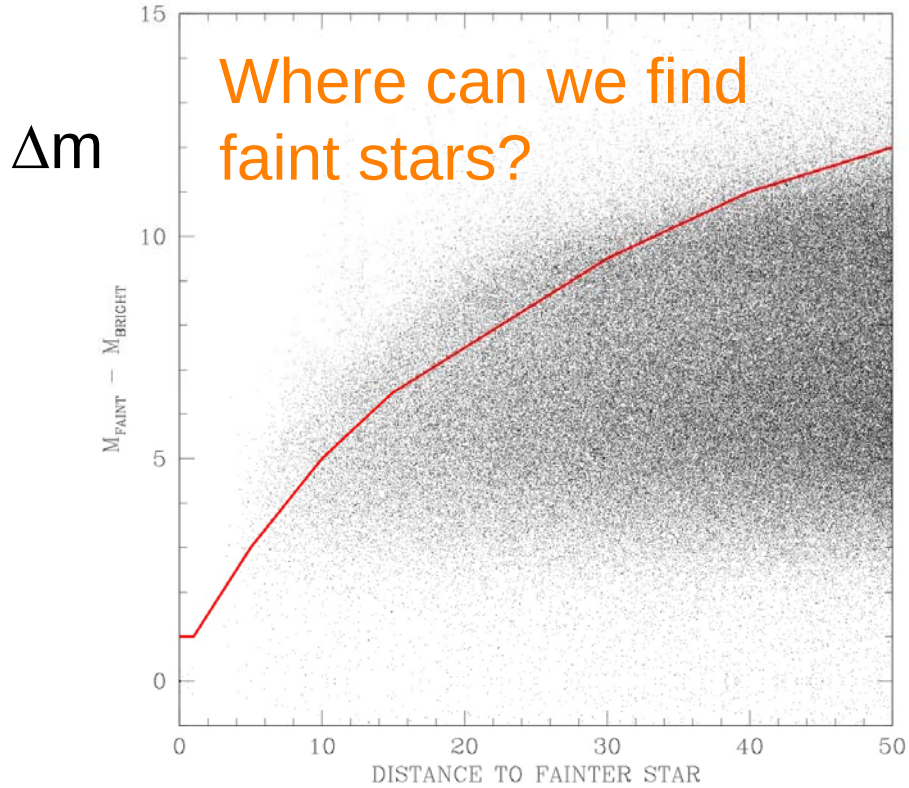


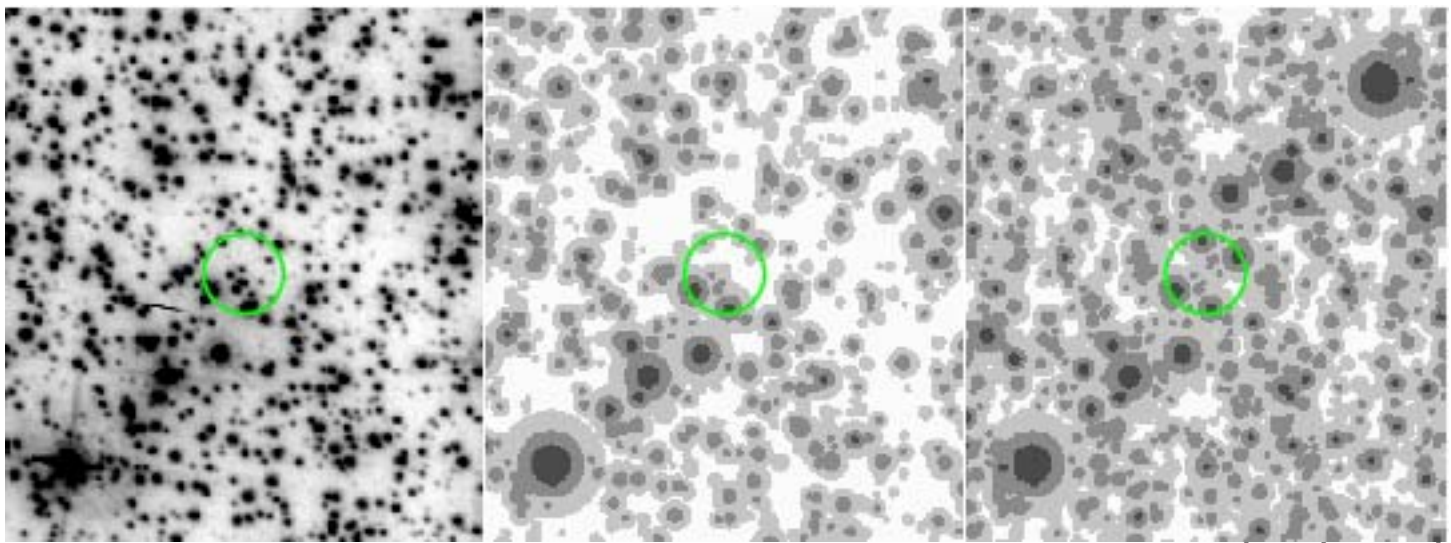




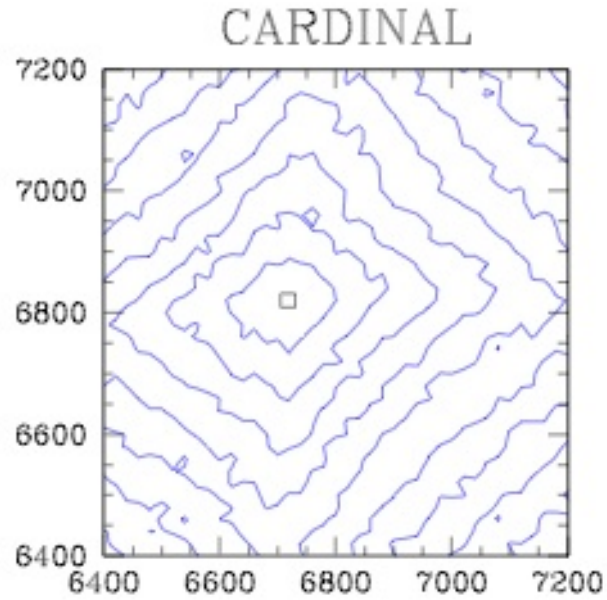
Method 2 Finding the center using pie slices

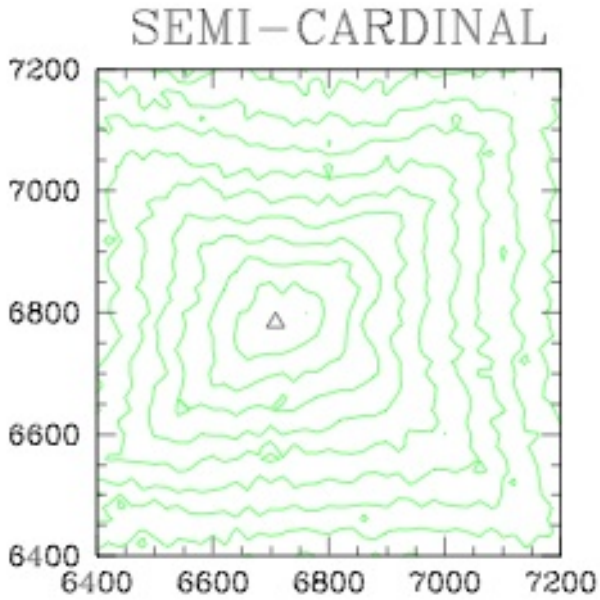
Issue: small-number statistics of bright stars

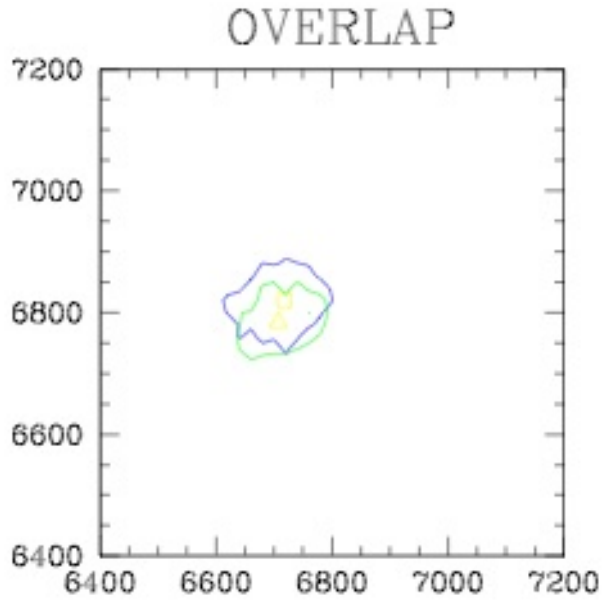




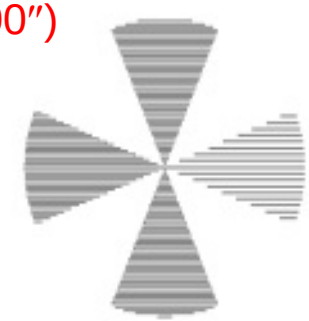
Central region | Finding mask | Symmetrized mask

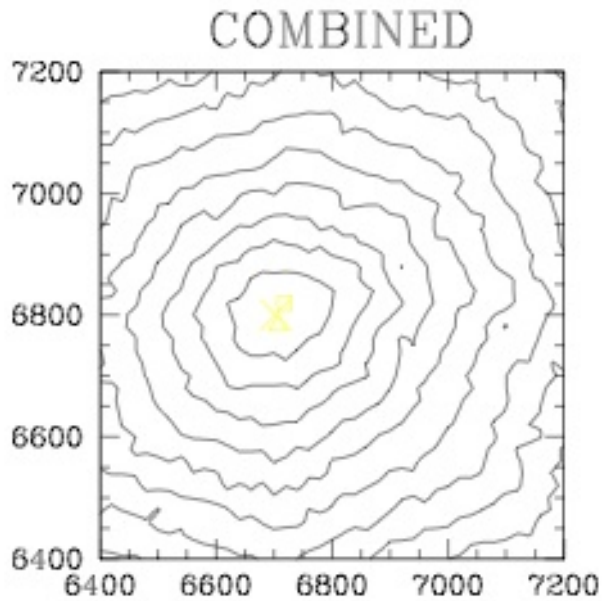






(Slices went out to 200″)





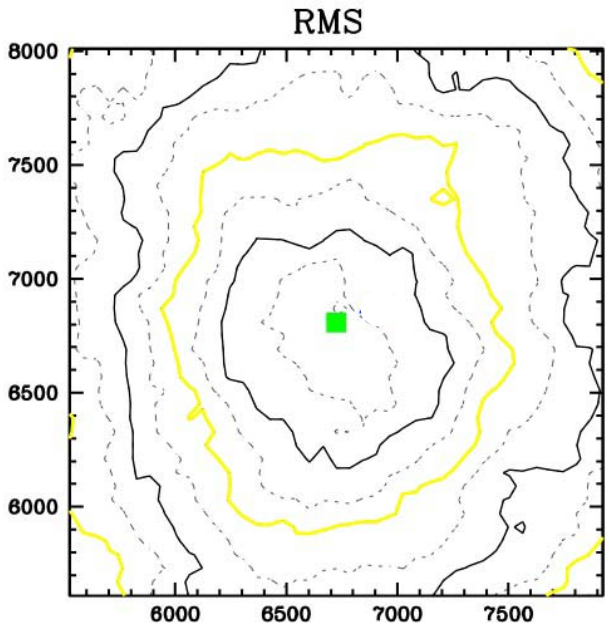
Centers agree to ~2″, so the average should be good to ~1″ (235,000 stars)

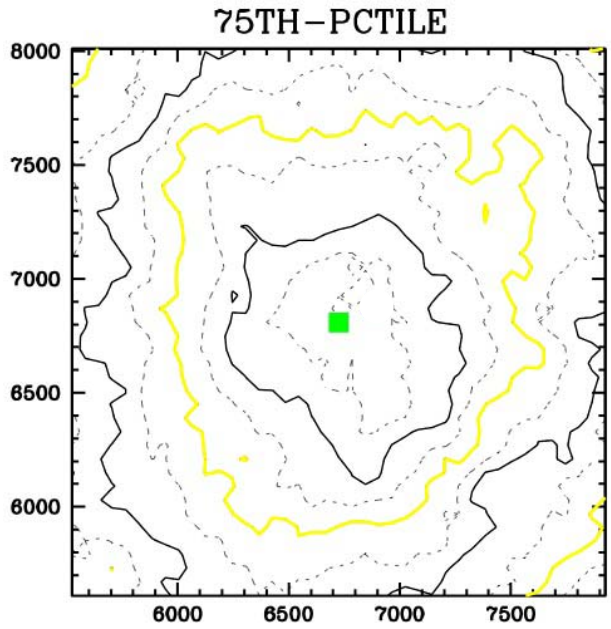
Agree to 0.25″ with contour center

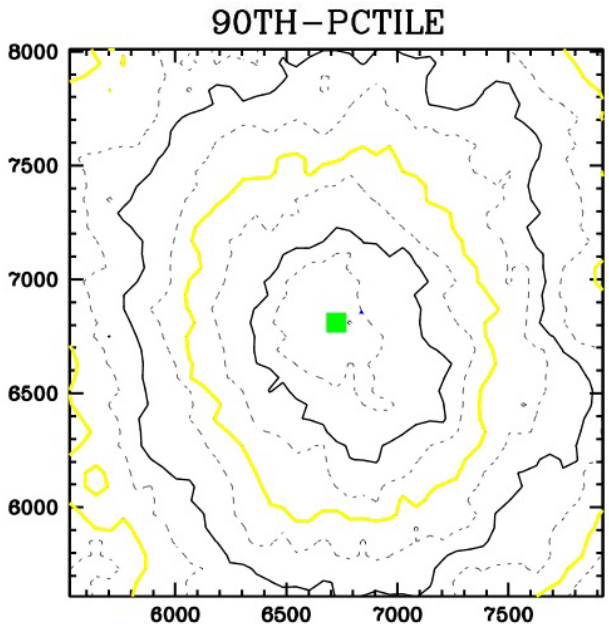
Method 3 Finding the kinematic center

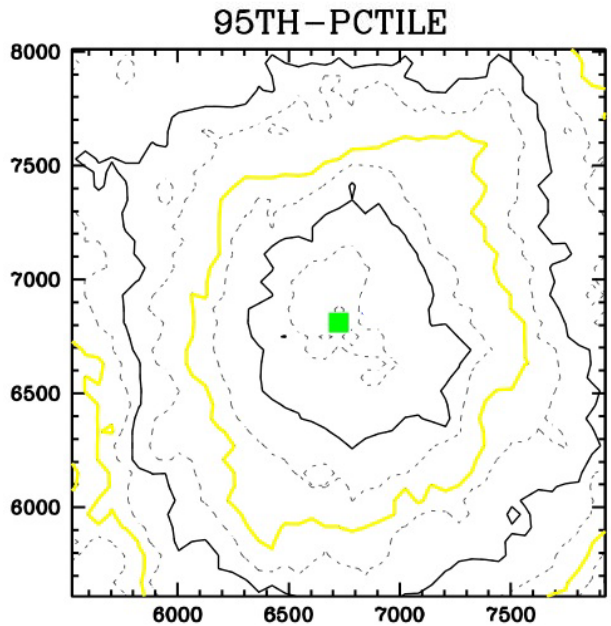
Calculate velocity dispersion at various locations

Needed contours to 1%, So needed 4500 stars, 600 pixel radius









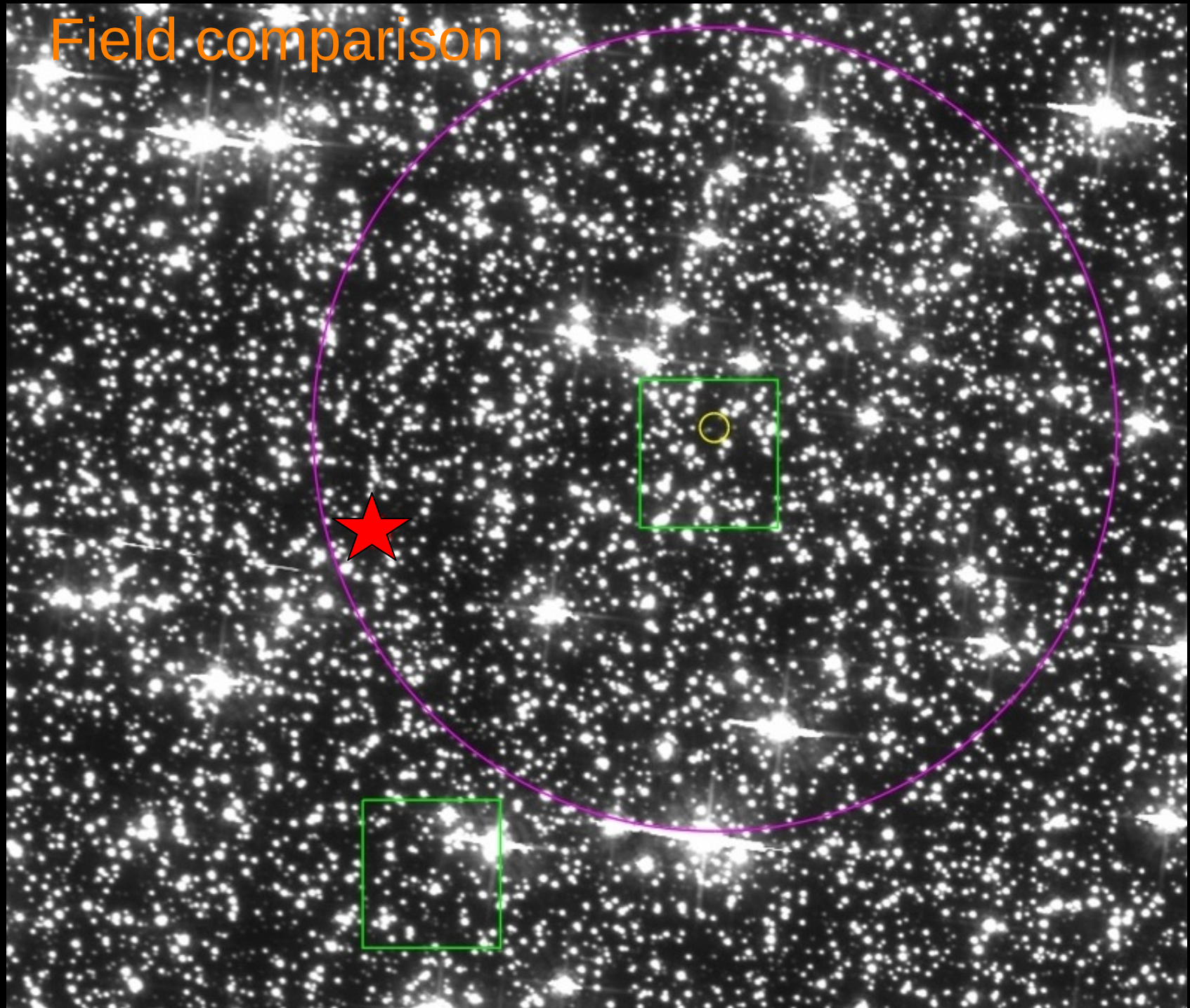
Bored yet?

- Our center: (13:26:47.24 , –47:28:46.5)
  - absolute calibration from 2MASS*
- Why so much emphasis on center?

- Strong disagreement with previous centers:
  - Harris catalog $\Delta\alpha = -14.3''$ $\Delta\delta = +7.5''$ (16″)
  - Castellani+ 2007 $\Delta\alpha = -15.1''$ $\Delta\delta = +3.6''$ (15″)
  - NGB08 $\Delta\alpha = -11.9''$ $\Delta\delta = +3.6''$ (12″)

Internal agreement is ~ 4″,
but off by ~ 14″ from this determination!

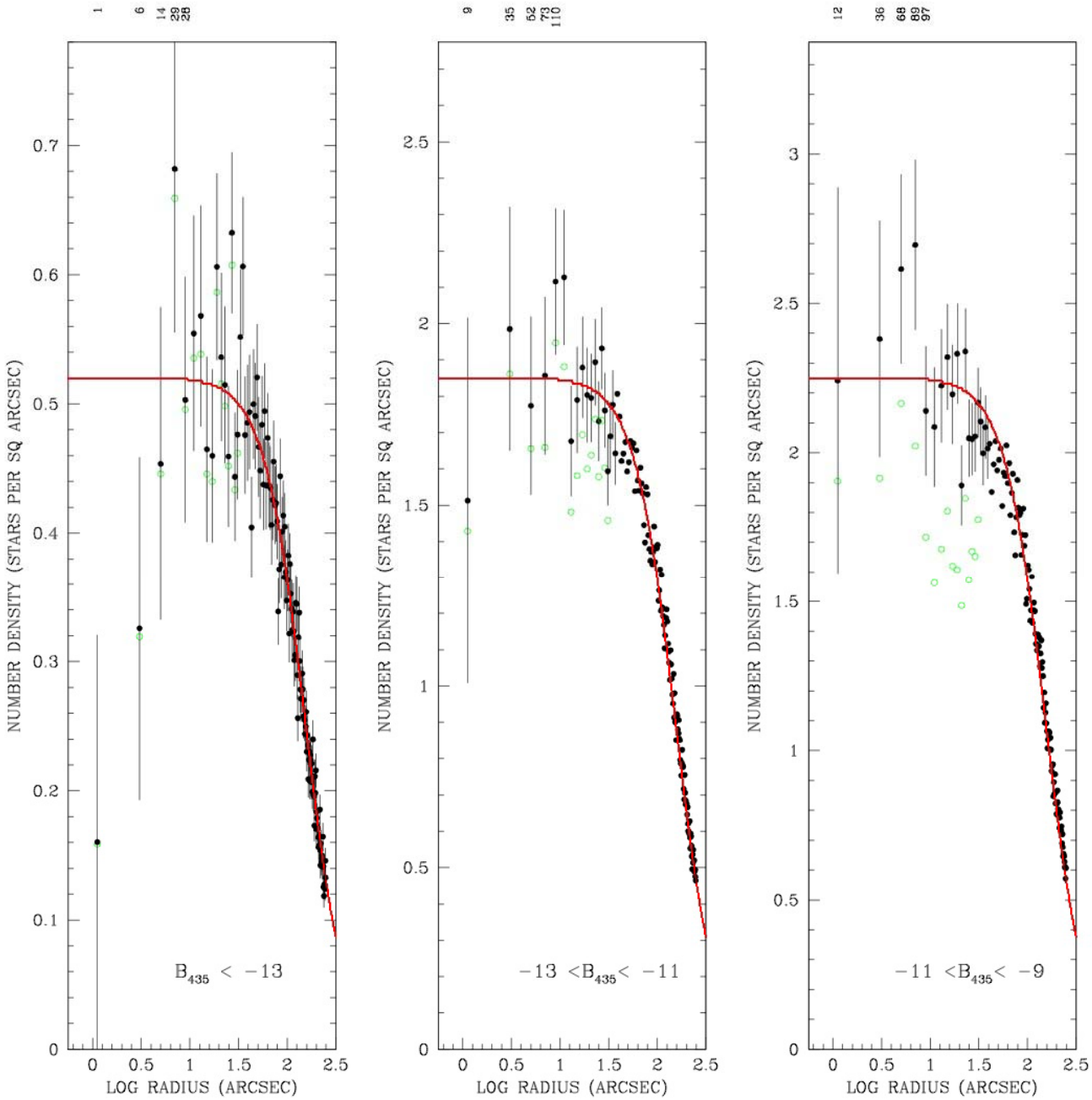
(For reference, r_{BH} ~ 5″ for 10,000 M_{SUN} IMBH)


Field comparison

Surface-density profile

May not fit King model perfectly, but no need for a sharp cusp

Consistent with being flat within 20″



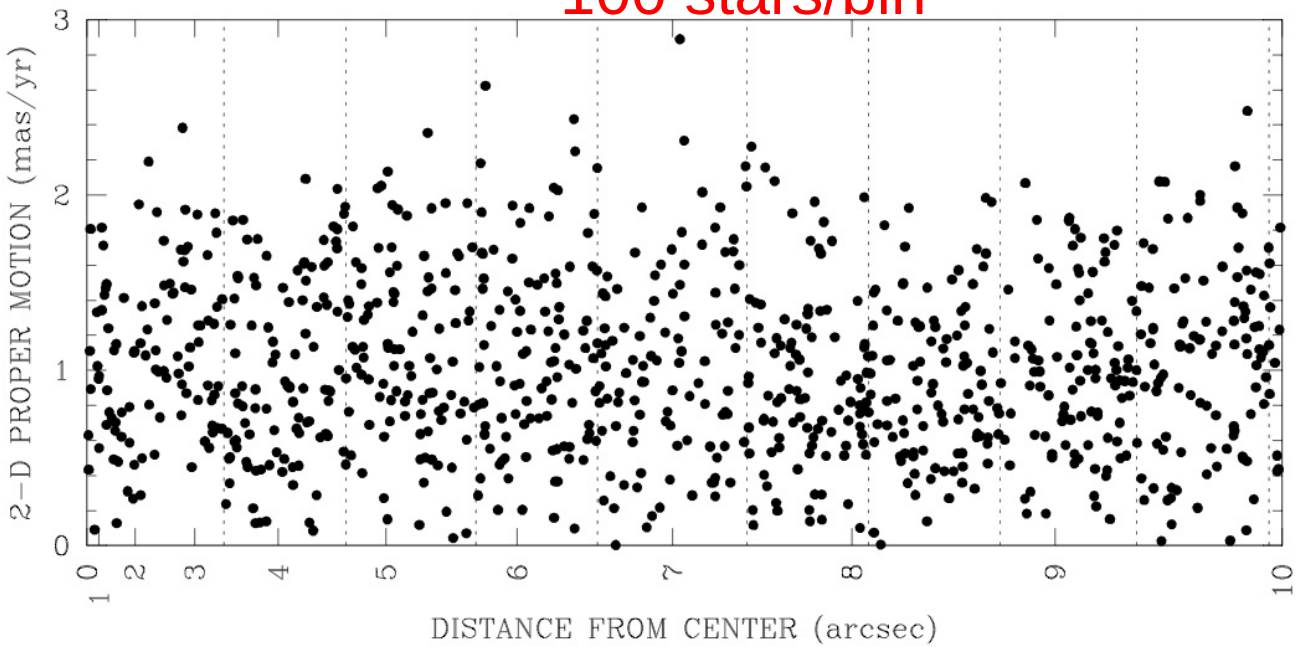
Turnoff Just below TO S/N ~ 100

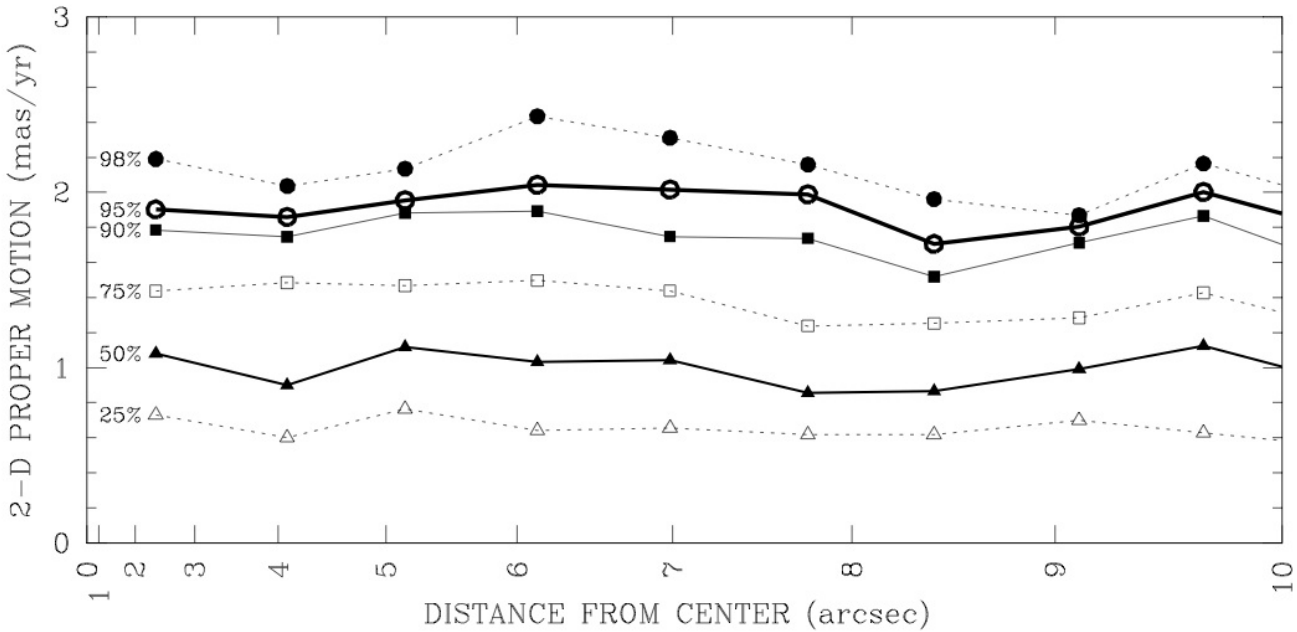
PM Profile

Total motions of the stars in the inner 10″

Motions at the center are consistent with those at 10″

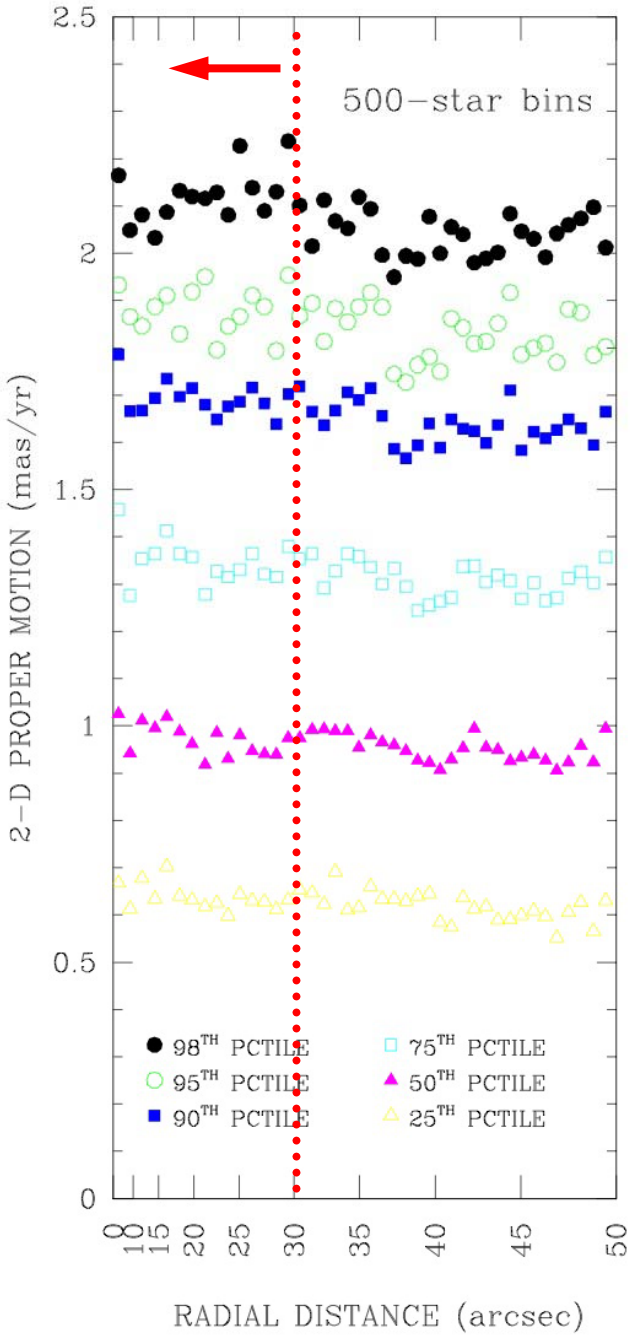
100 stars/bin

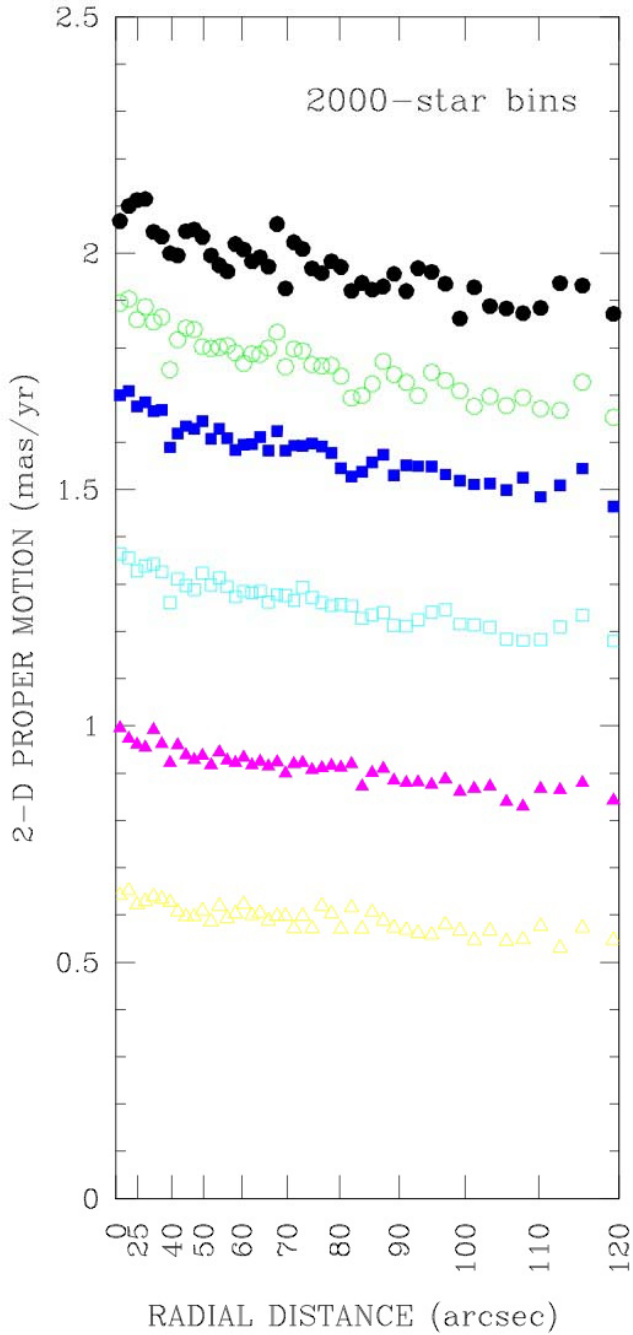




Velocity Profile with R

- Overall upward trend toward center
- But, it is consistent with being flat within 30″





Back of the Envelope: The closest star

- $\Sigma = 3/\square''$ — density of well-measured stars
- $\rho = 0.006/(\text{''})^3$ — 3-D density
- $\rho =$ 500 stars /pc^3 — D ~ 4700 pcs
- $r_* \sim$ 0.08 pc, or 17,000 AU — distance to closest star
- $v^2 \sim GM_{BH}/r_*$
- For… 10,000 M_{SUN} BH: v ~ 55 km/s
  40,000 M_{SUN} BH: v ~ 110 km/s
- We see **one** star with v ~ 60 km/s

… screams out for a complete dynamical model!

Fitting a Dynamical Model

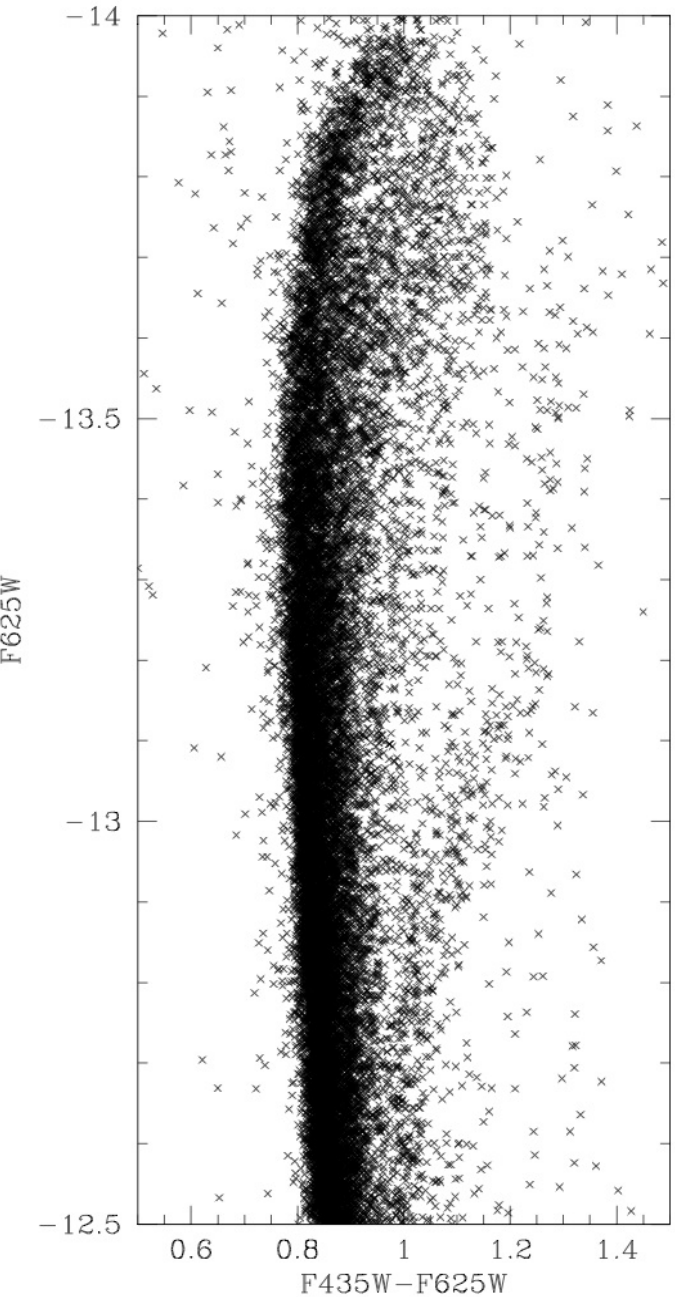
- Disclaimer
- Fit Jeans equations to:
  - $\Sigma(R)$ surface-density profile this + Trager
  - $\mu(R)$ proper-motion profile this + vL
  - $V_{l.o.s.}(R)$ l.o.s.-velocity profile vdV compilation
  - $\beta(R)$ anisotropy profile this + vL

Jeans-Model Results

- Flat $\Sigma(R)$ profile ok, but cusp also allowed
  - depends on fitting radius: $\gamma = 0.00 \pm 0.07$ (R<15″)
    $\gamma = 0.05 \pm 0.02$ (nuker)
- Flat central velocity slope: -0.06 ± 0.08 km/s/″
- Anisotropy: ~5% radial in core observed
- Gauss-Hermite moment $h_4 = -0.024 \pm 0.006$
  - flat topped, but less extended wings
- 3 models:
  - flat core + isotropy: not allowed (cen disp, h_4)
  - flat core + anistropy: no dark matter needed
  - cusp + isotropy: 10,000 M_{SUN} BH / dark matter

Future…

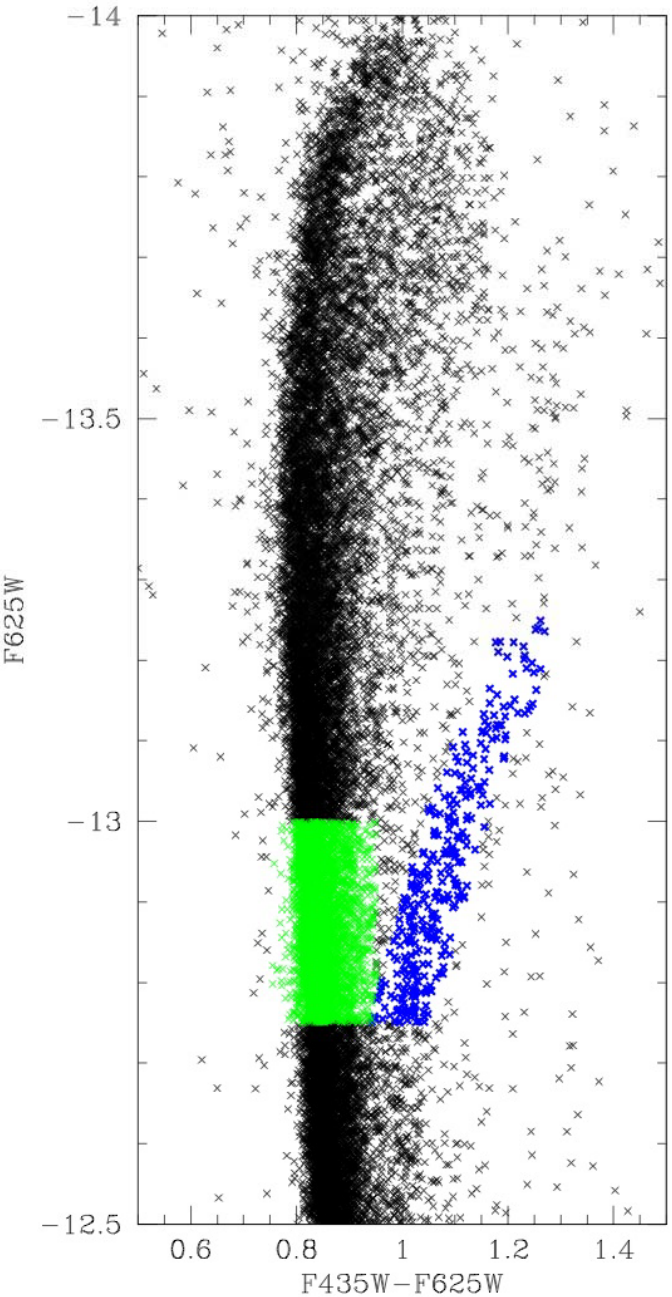
- More sophisticated models
- Better radial coverage $V_{l.o.s.}(R)$ and $\Sigma(R)$
- Other clusters
  - HRC/HRC/HRC data in hand & coming…
    - NGC2808, NGC6341, NGC6752
  - HRC/WFPC2 data in hand & coming for…
    - NGC6624, NGC7078, NGC0362, NGC6681, NGC7099
  - see Justice Bruursema's poster…

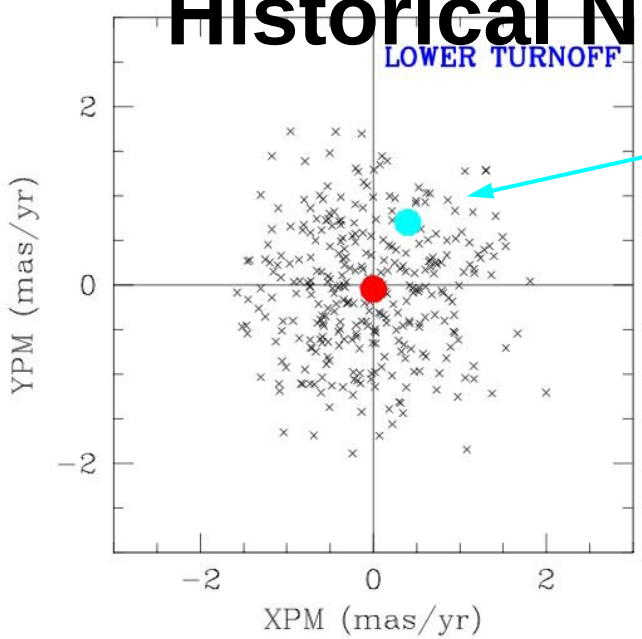


Historical Note

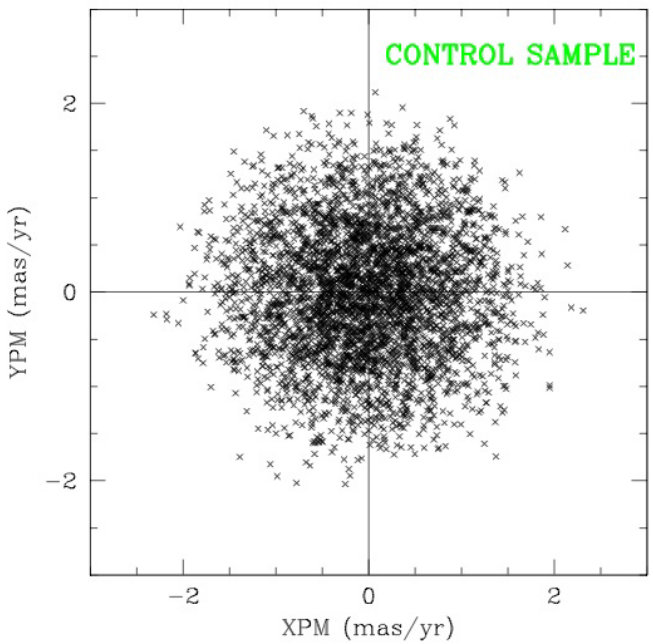
Using, van Leeuwen 2000 PMs, Ferraro et al 2002 found the RGB-a stars to be moving relative to the bulk cluster

Historical Note





Ferraro et al 2002



…in agreement with Bellini et al (in press)