Proper Motions with WFIRST

Kailash C. Sahu
Space Telescope Science Institute
Baltimore.

WFIRST Field: ~90 times HST/ACS FOV; ~200 times HST/WFC3 IR FOV

Microlensing Observations: ~6 (or 7) * 72 continuous days

10 pointings in the Galactic bulge

Integration time in W149: 52 sec, one observation every 15 minutes

Integration time in Z087: 290 sec; one observation every 12 hr.

Expected Accuracies in Proper Motion Measurements

Measurement Uncertainty in the position of a point source:

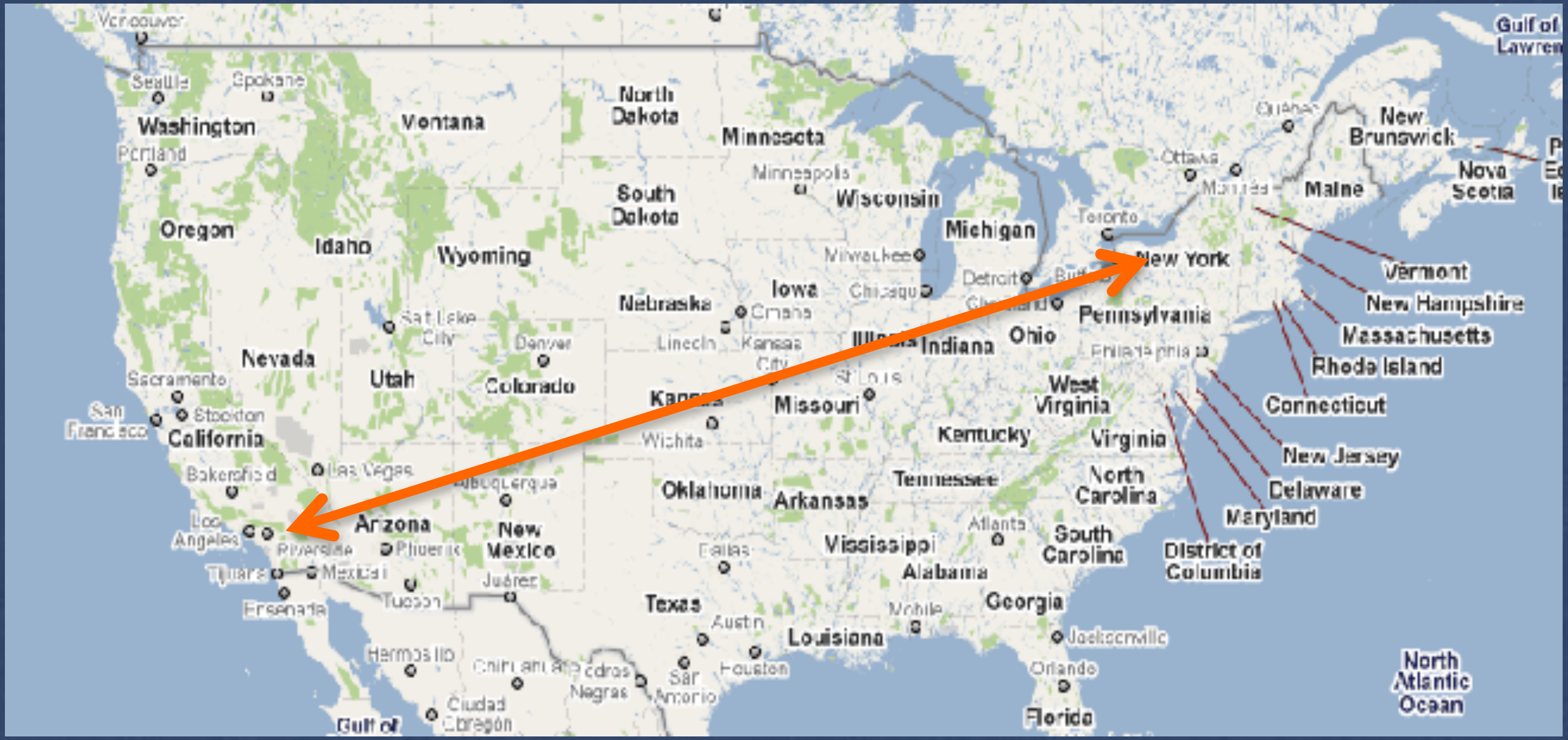
$\Delta \sim \mathrm{FWHM}/(S/N)$

FWHM ~ 0.1 arcsec

Counts in a single measurement for a star with V ~20: > 10,000

S/N ~100

Positional uncertainty ~ 0.1 arcsec/100 ~ 1 milliarcsec

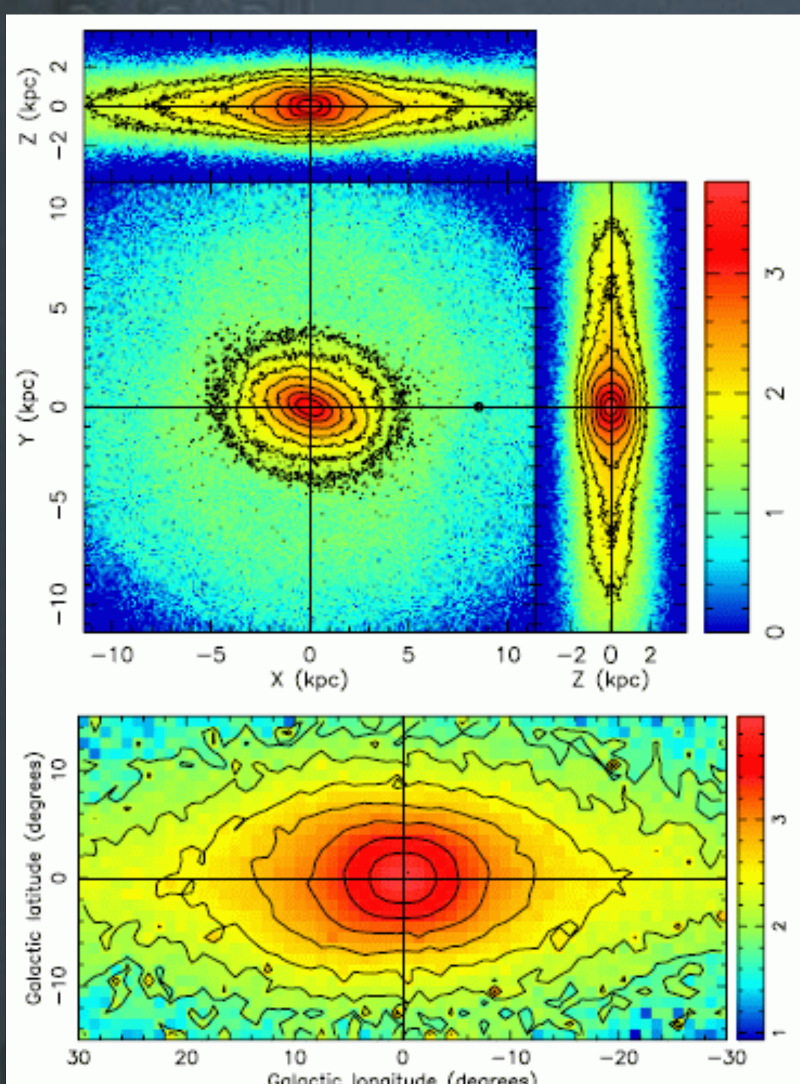


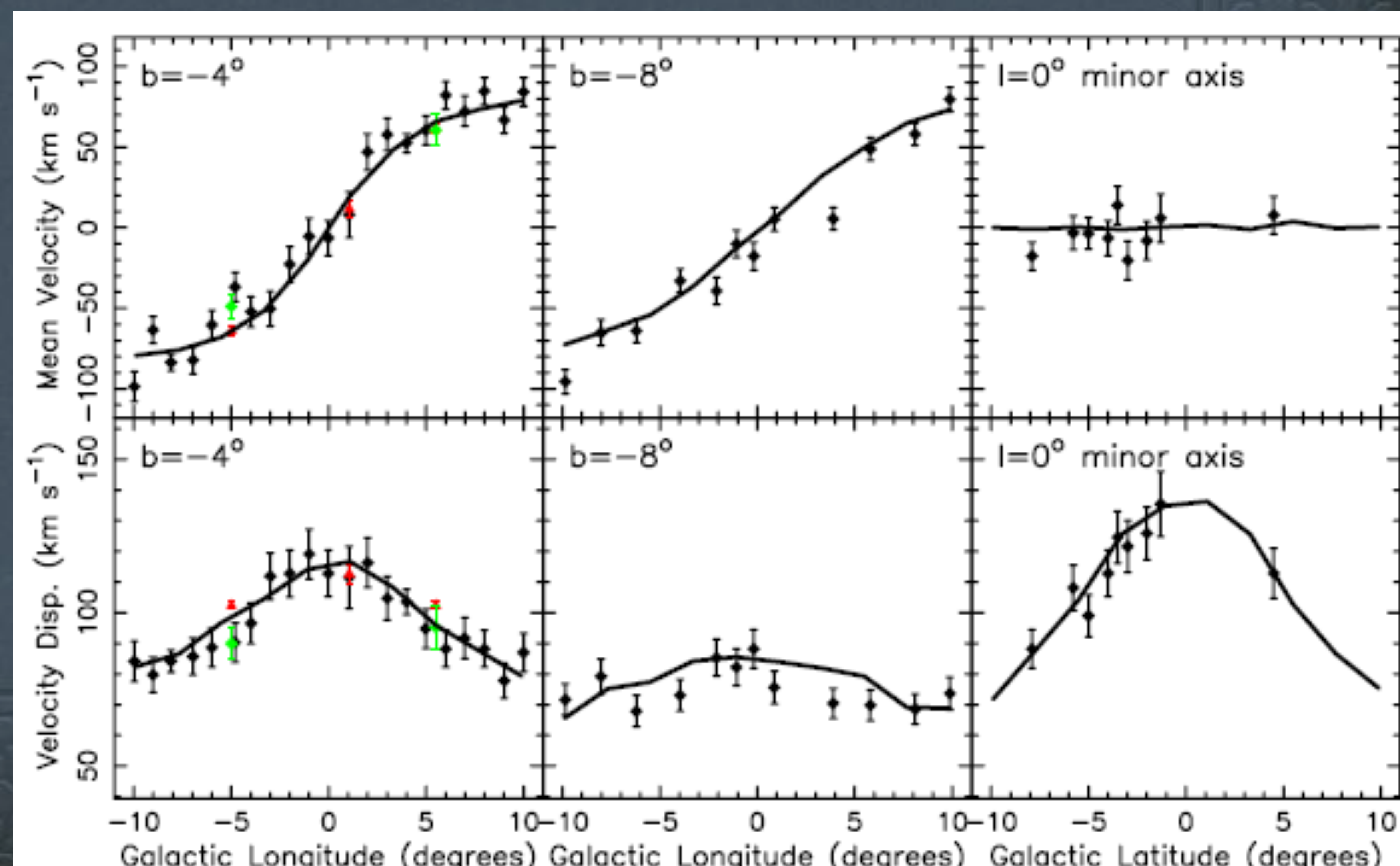
Sitting in LA, this corresponds to measuring an insect moving by the width of an US quarter.

Accuracy increases further with the number of observations by √N.

Earlier PM Measurements of the Bulge

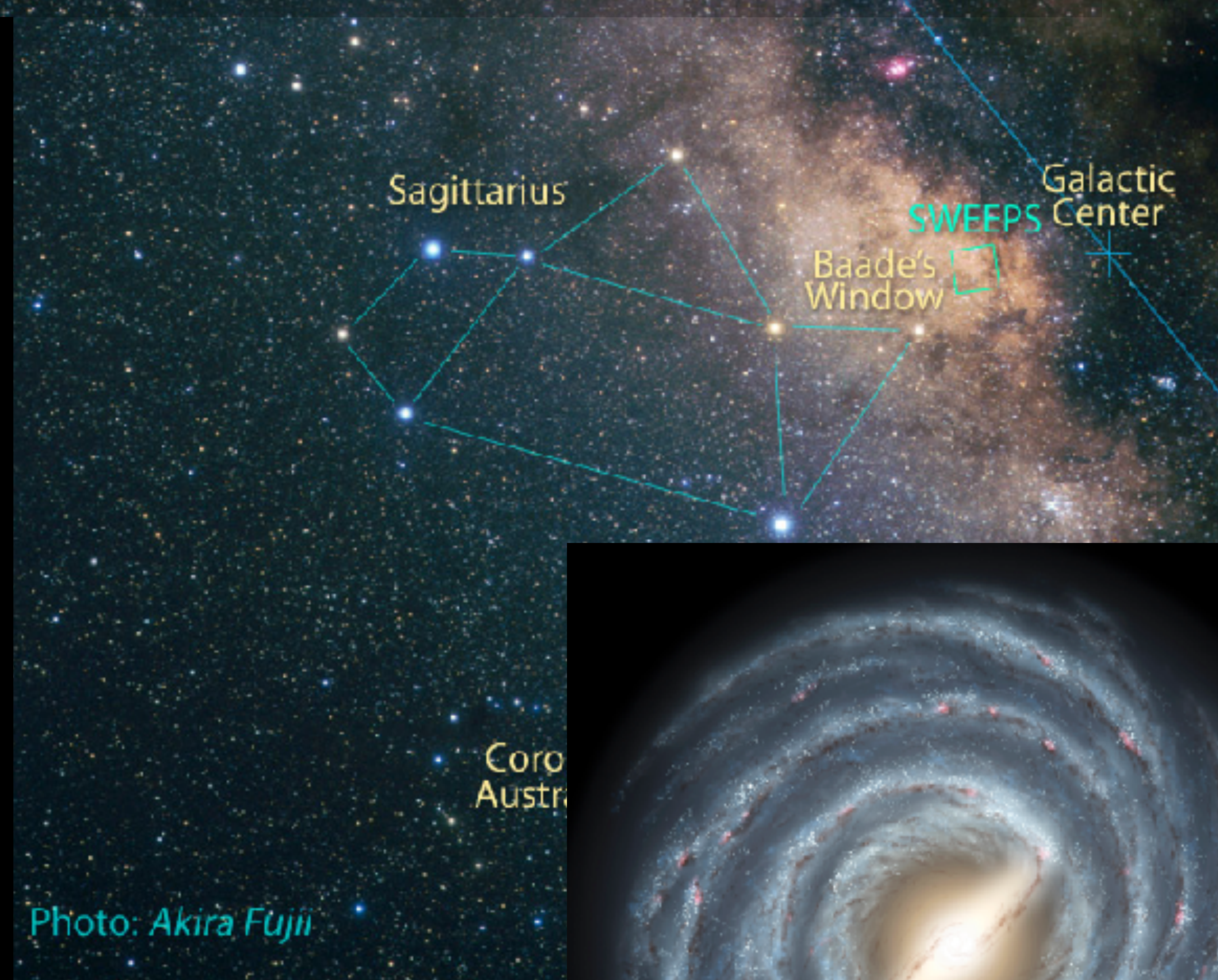
- OGLE-II: PMs of ~10^6 stars with a precision of 0.8-3.5 mas yr^{-1} (Eyer & Wo´zniak 2001; Sumi et al. 2004)
- Space-based PMs: a number of studies of clusters that use PMs to discriminate the cluster from the field.
- Kuijken & Rich (2002): HST observations to bulge proper motion studies,
- Stank Window: poster outside
- PMs from Microlensing follow-up observations with HST
- RV measurements by BRAVA collaboration
- PM measurements from SWEEPS Transit and microlensing studies

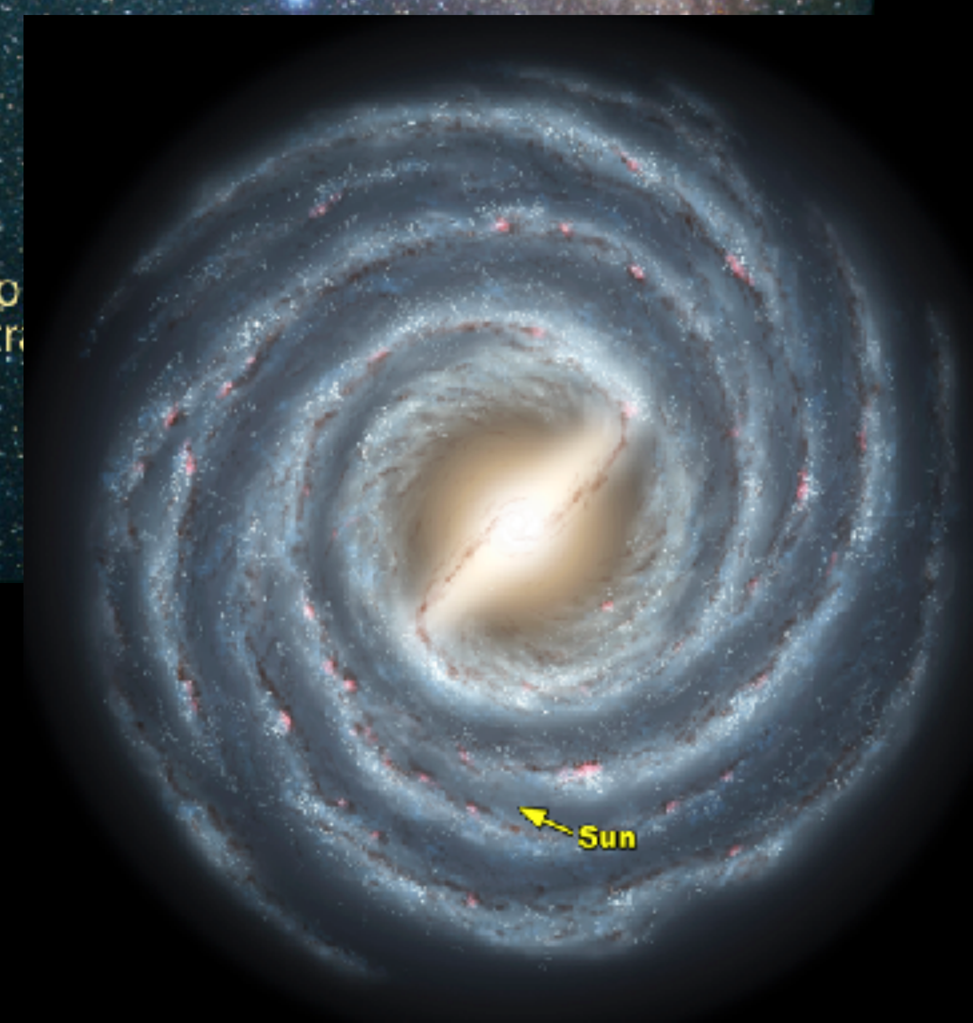




Why study Proper Motions in the Bulge?

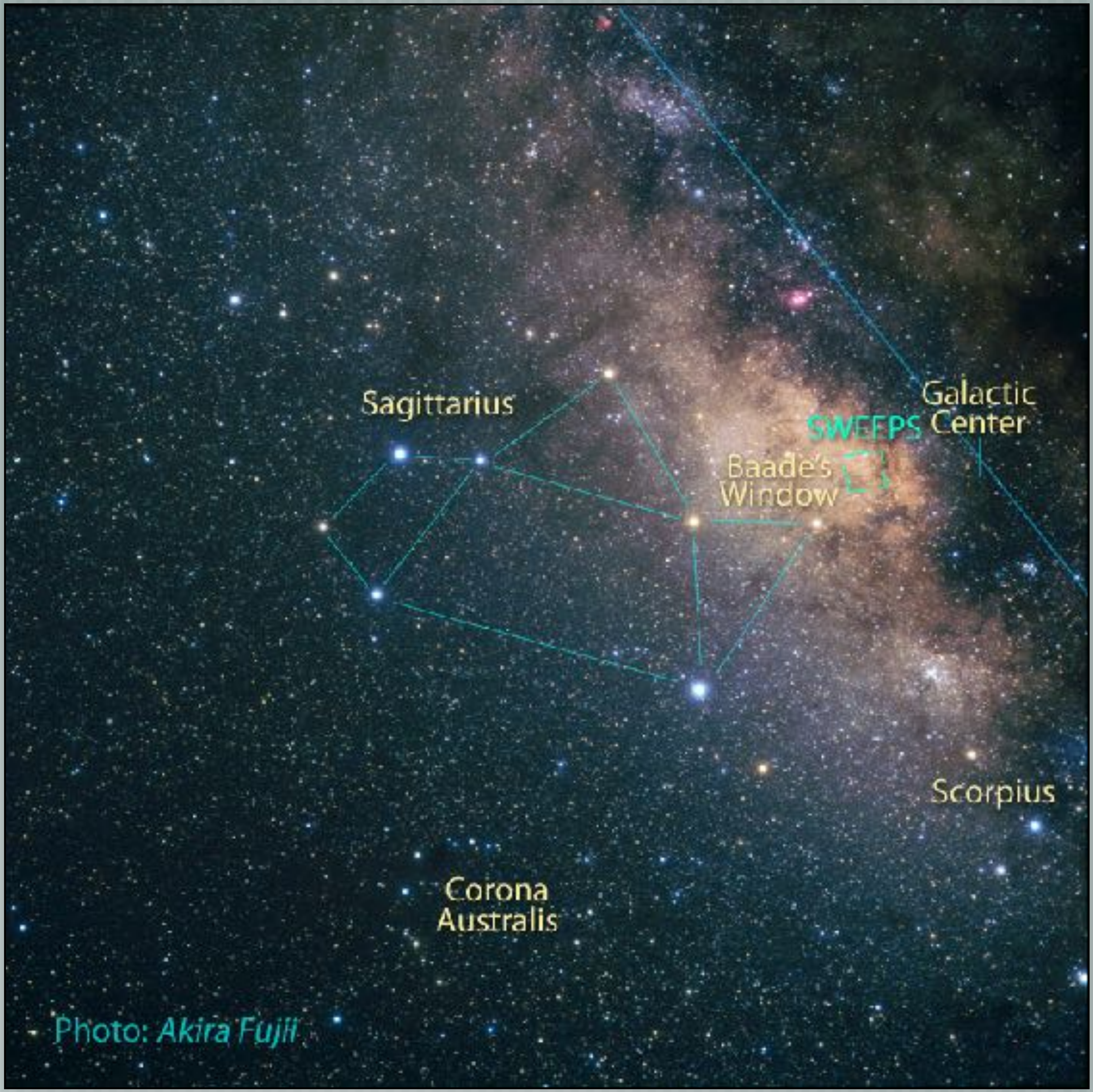
- A key galactic component
  - About 15-20% of the Milky Way stars
  - When we look towards the bulge, we also see a large population of disk objects
  - For ~75% of the microlensed source stars in the Bulge, location can be confirmed
  - Many projects, such as
    - Blue stragglers
    - IMF
    - WDs



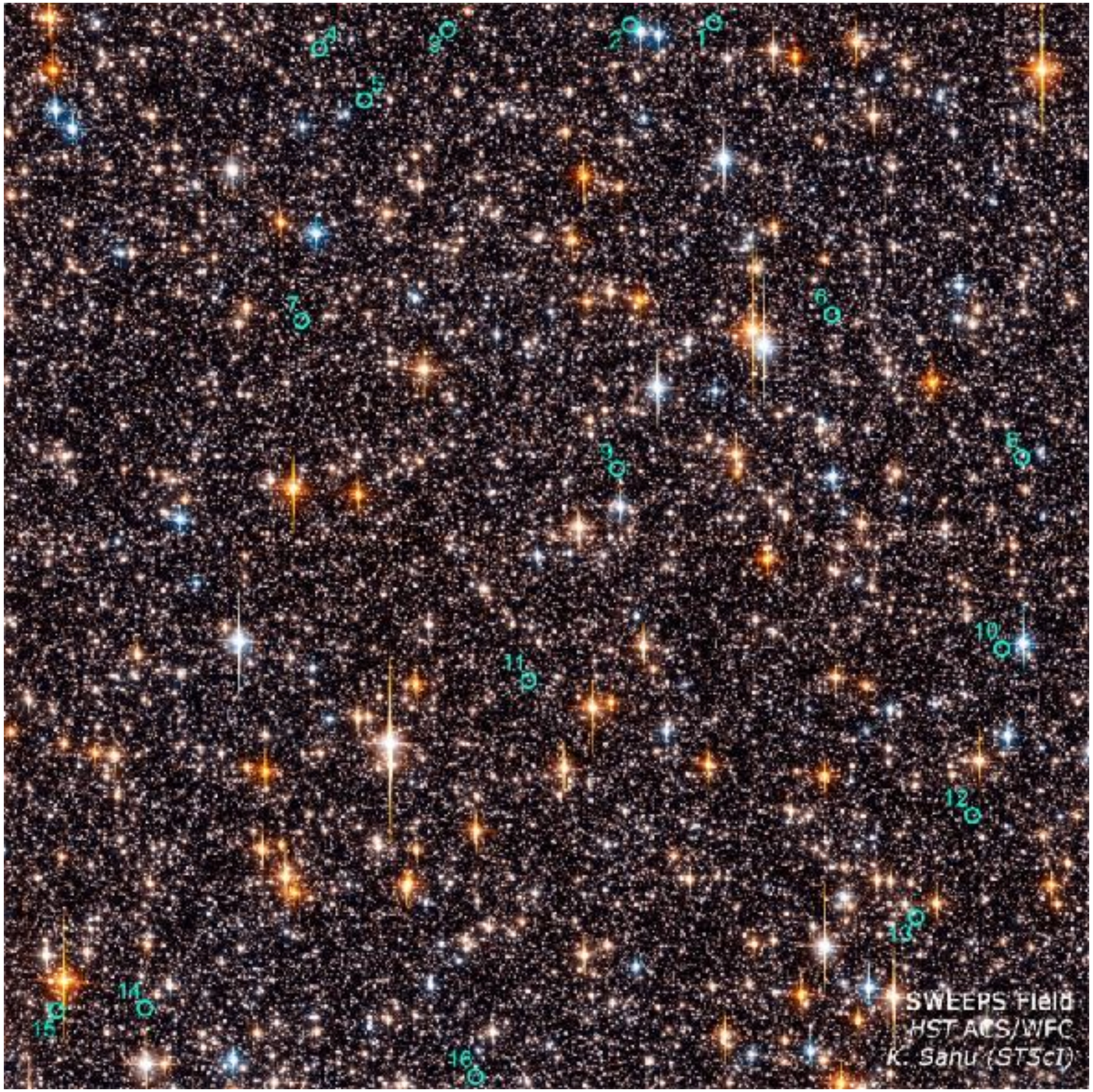


SWEEPS Project (Saggitarius Window Eclipsing ExoPlanet Search)
(Sahu et al. 2004, Nature, 443, 1038)

- Location of SWEEPS field
- Ideal for studying some key questions
- Monitored this field continuously for 7 days



SWEEPS Project



Sagittarius Window
Eclipsing Extrasolar
Planet Search

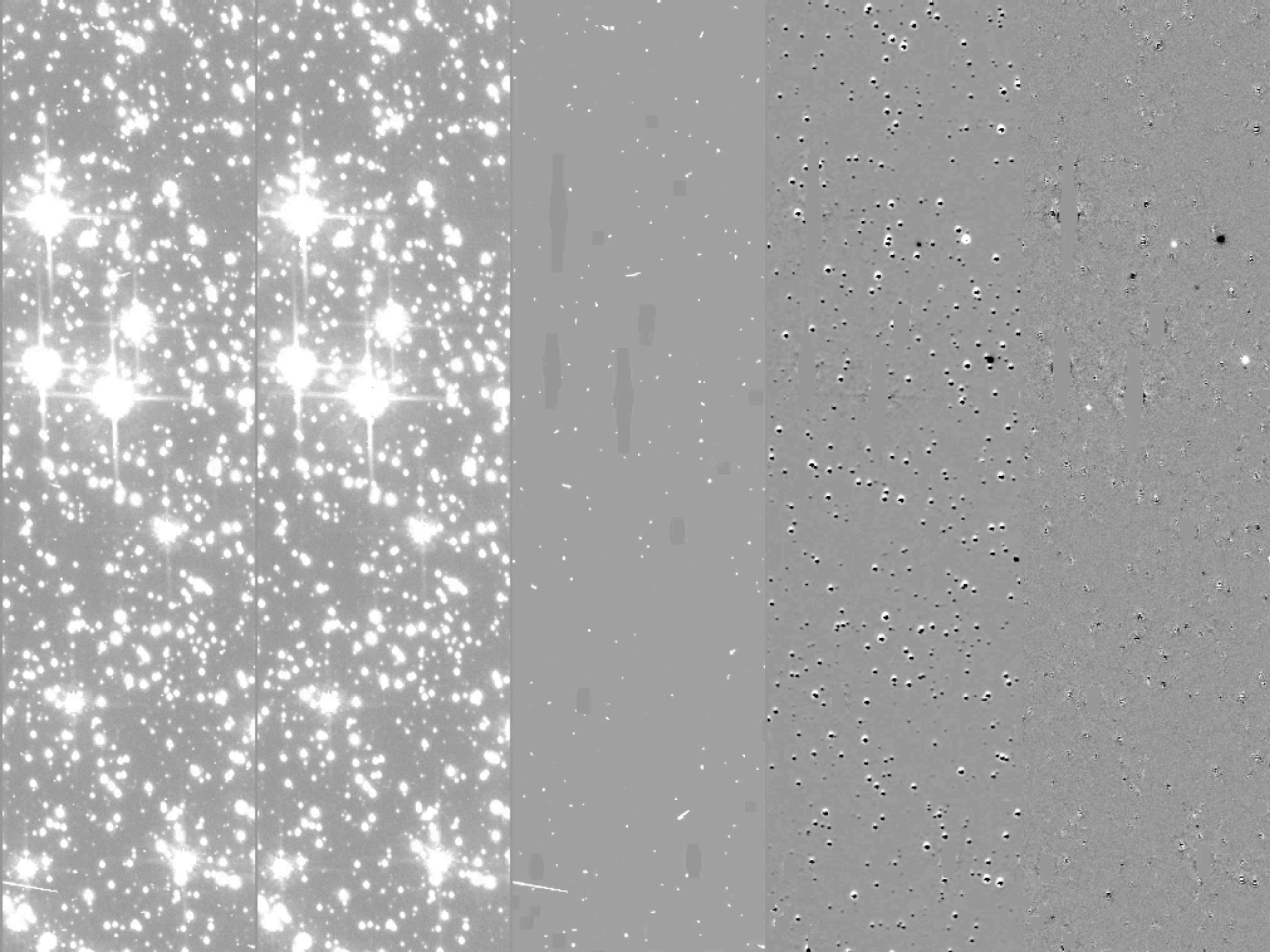
202”x202”
Continuous monitoring
for 7 days

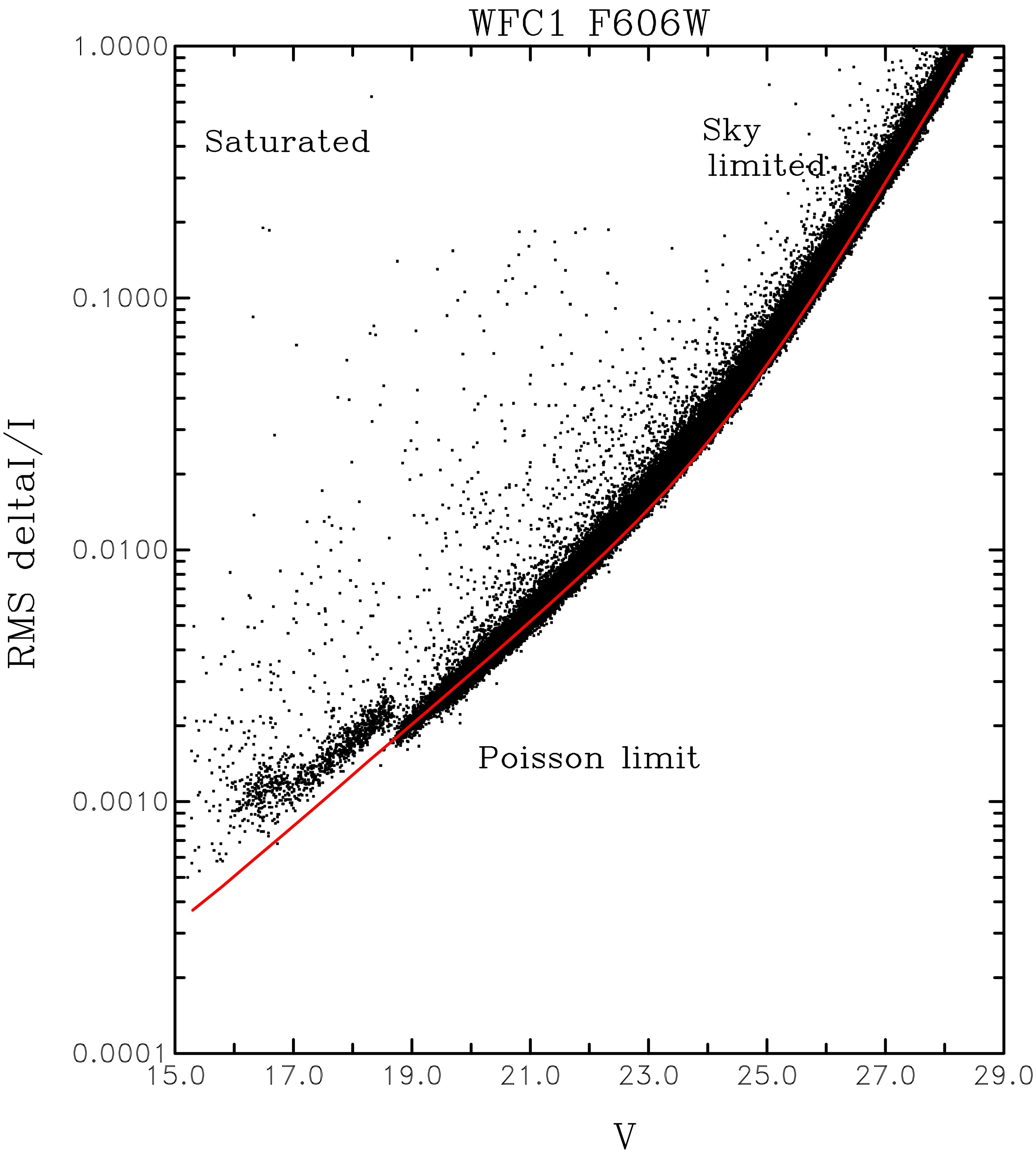
180,000 stars to V ~ 27.
245,000 stars to V ~ 30

265 I images
254 V images
339 sec Int. time

No transits missed

Deepest Galactic field



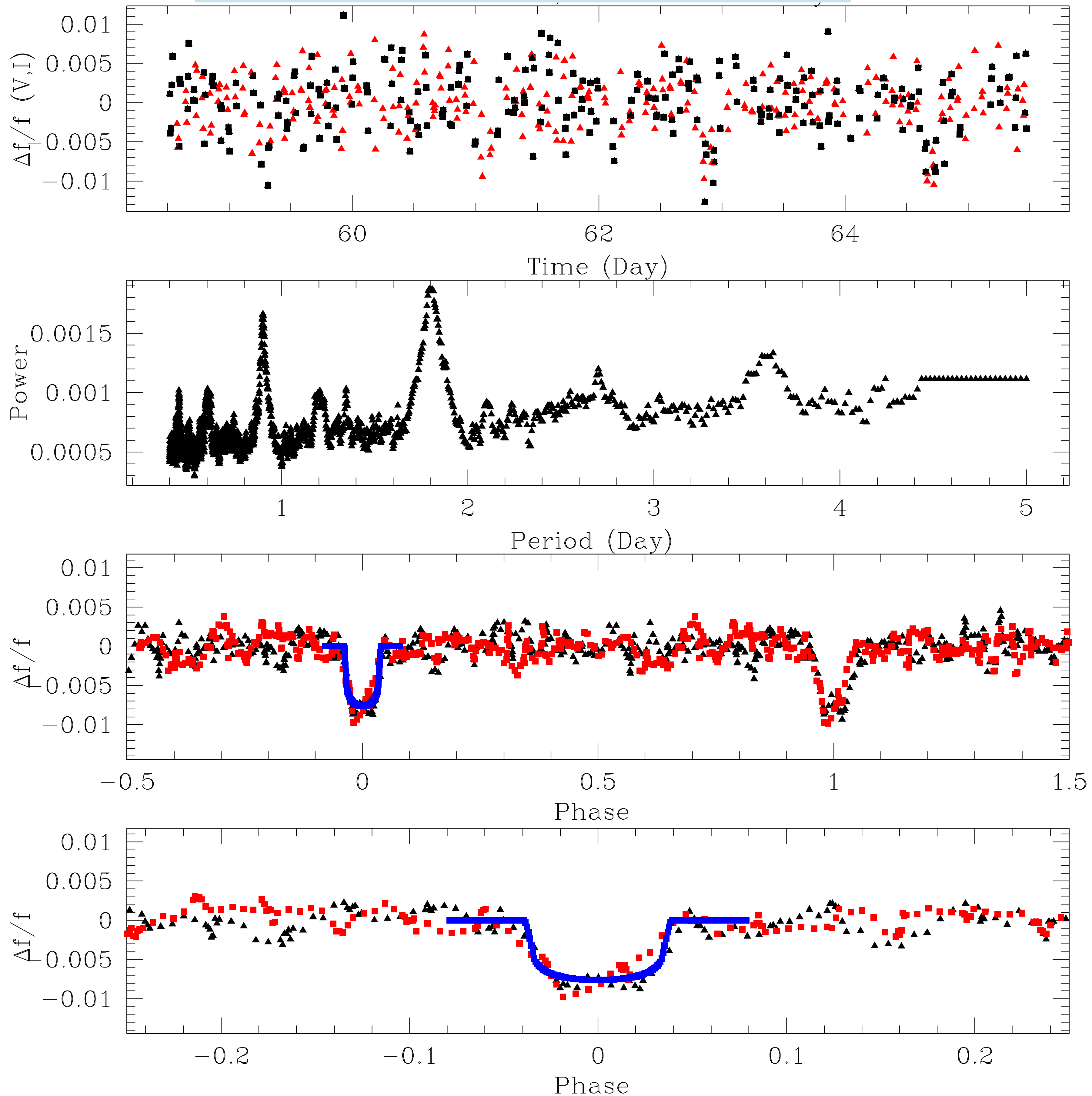


Noise is close to Poisson limit for unsaturated stars.

Slightly higher for saturated stars.

Sensitive to detecting Jovian planets to V~26 (corresponding to 0.44 $M_\odot$).

SWEEPS-11, V~19.6, P=1.8d, RV confirmed

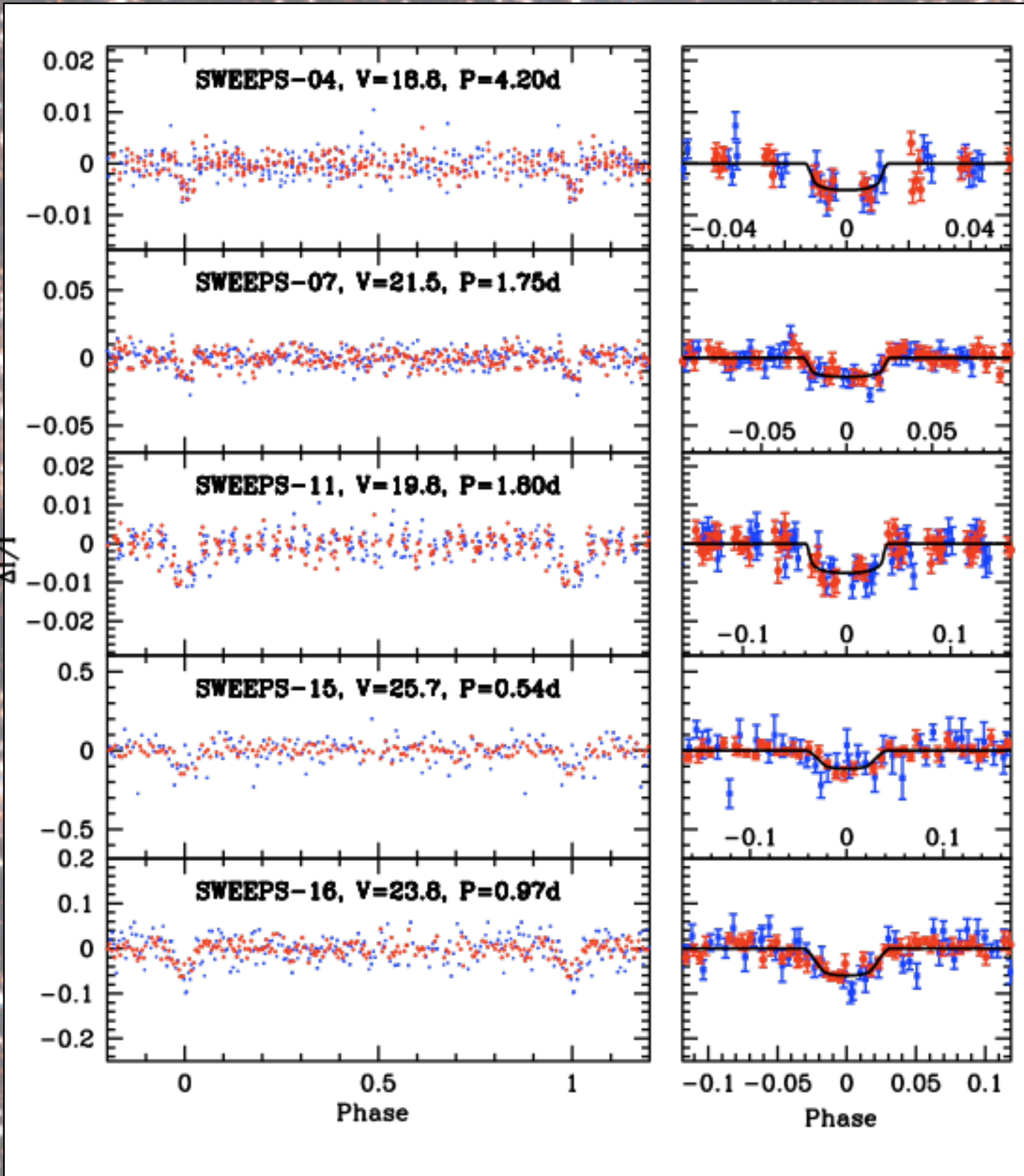


Raw data
Black: V
Red: I

Box-fitting power spectrum
S/N > 5

Folded data
Light curve fitting
S/N(PSF) must be >6.5

Expanded view of transit



We discovered 16 Planetary Candidates.

Example light curves

Blue: V-band

Red: I-band

Black: Model fit

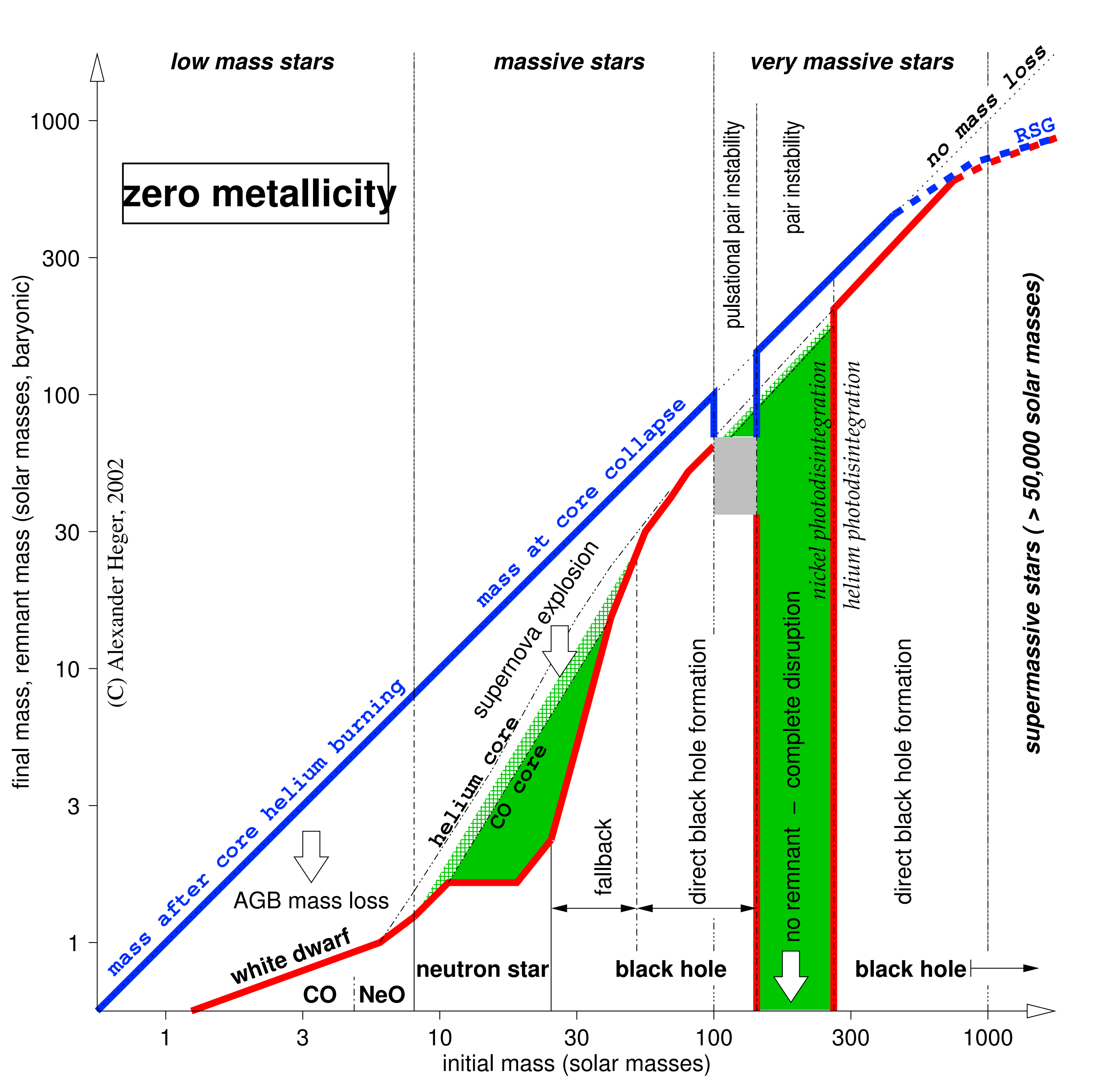
Includes:

Two RV-confirmed planets (SWEEPS-04 and SWEEPS-11).

This program provided the first epoch of deep observations for PM study of the bulge.

Isolated Black Holes Through Microlensing

- Stars with M > 20 M☉ are thought to end their lives as black holes. There should be 100 million BHs in the Galaxy.
- A large fraction of them are expected be isolated, because:
  - ~25% start as single stars
  - close binaries lead to merging during SN explosion
  - very wide binaries produce single BHs due to orbital separation by the "kick velocity".
- Yet, there has never been an unambiguous detection of an isolated black hole.
- Microlensing is the only method capable of detecting solitary BHs.



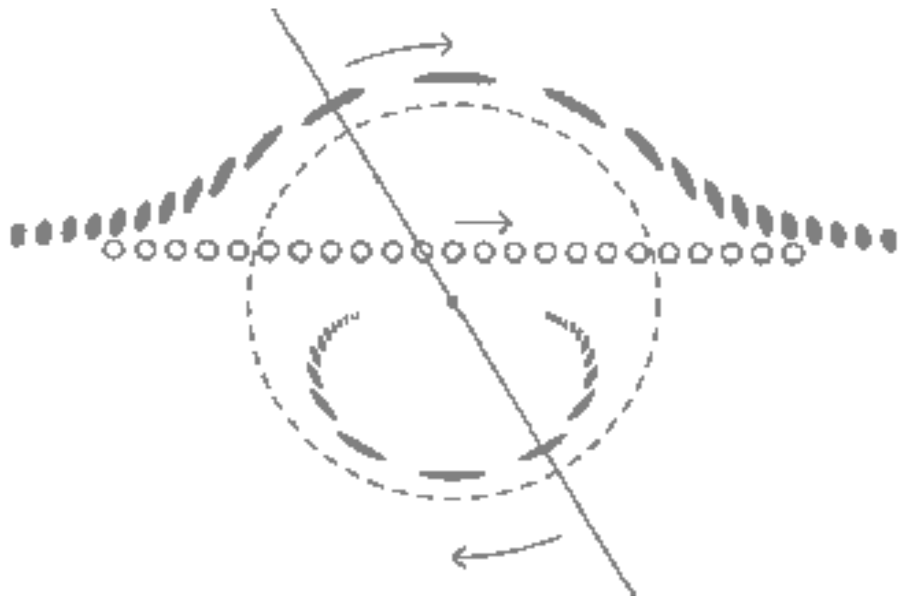
Initial-Final Mass Relation (Heger, 2010)

Mass discrepancy of stellar remnants

- **Masses of NSs and BHs in binary systems:**
  - **NS masses ~1.4$M_\odot$**
  - **BH masses ~8 +/- 1$M_\odot$**
- **Theoretical Models:**
  - **NS masses ~ 1.2–1.6$M_\odot$**
  - **BH masses 3 to 20 $M_\odot$**
- **LIGO observations: ~10-30 $M_\odot$**

- **Observed BH masses from binaries are a biased and minority sample**
- **HST programs can provide an unbiased mass and velocity distribution for isolated NSs and BHs, through microlensing.**

Stellar Mass Black Holes and Microlensing

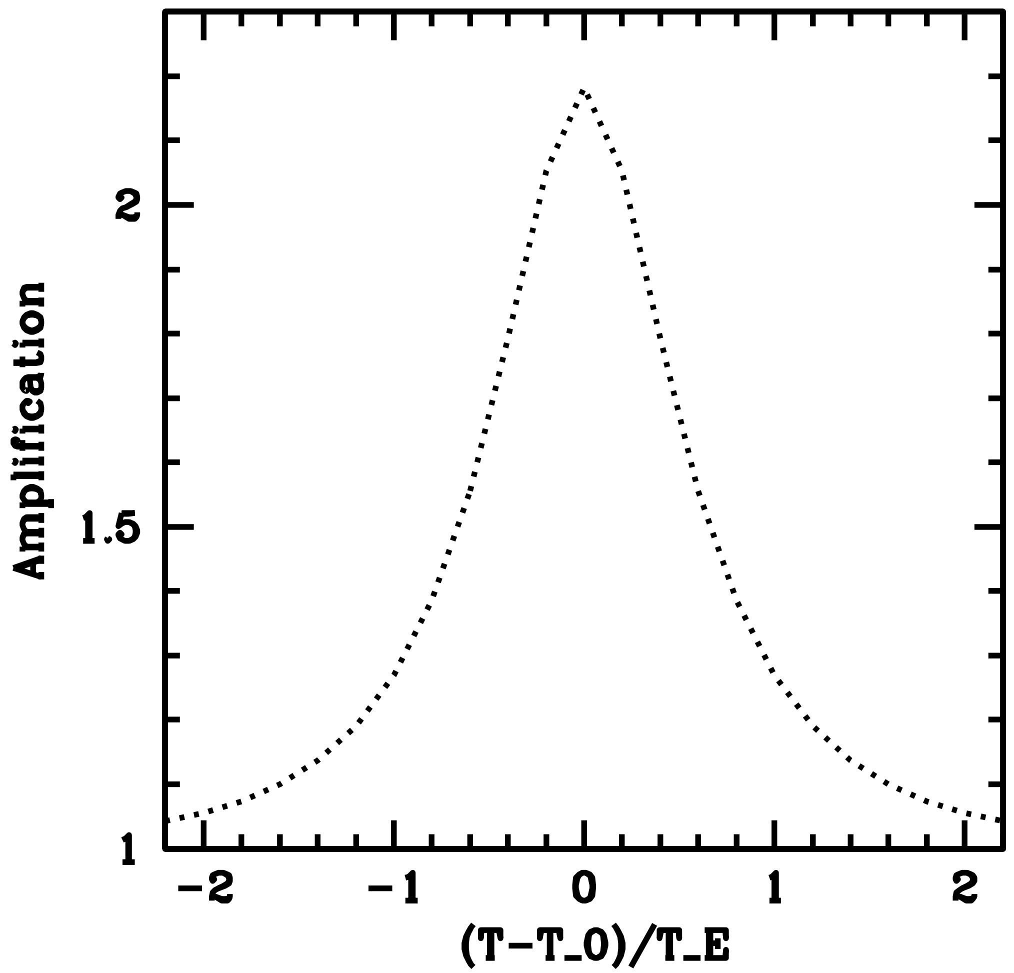


$R_E^2 = (4GM/C^2)\, D_L\, D_{LS}/D_S$

$T_E = R_E/V = [(4GM/C^2)\, D_L\, D_{LS}/D_S]^{0.5}/V$

$M_{lens} = (T_E\, V\, C)^2\, D_S/(4G\, D_L\, D_{LS})$

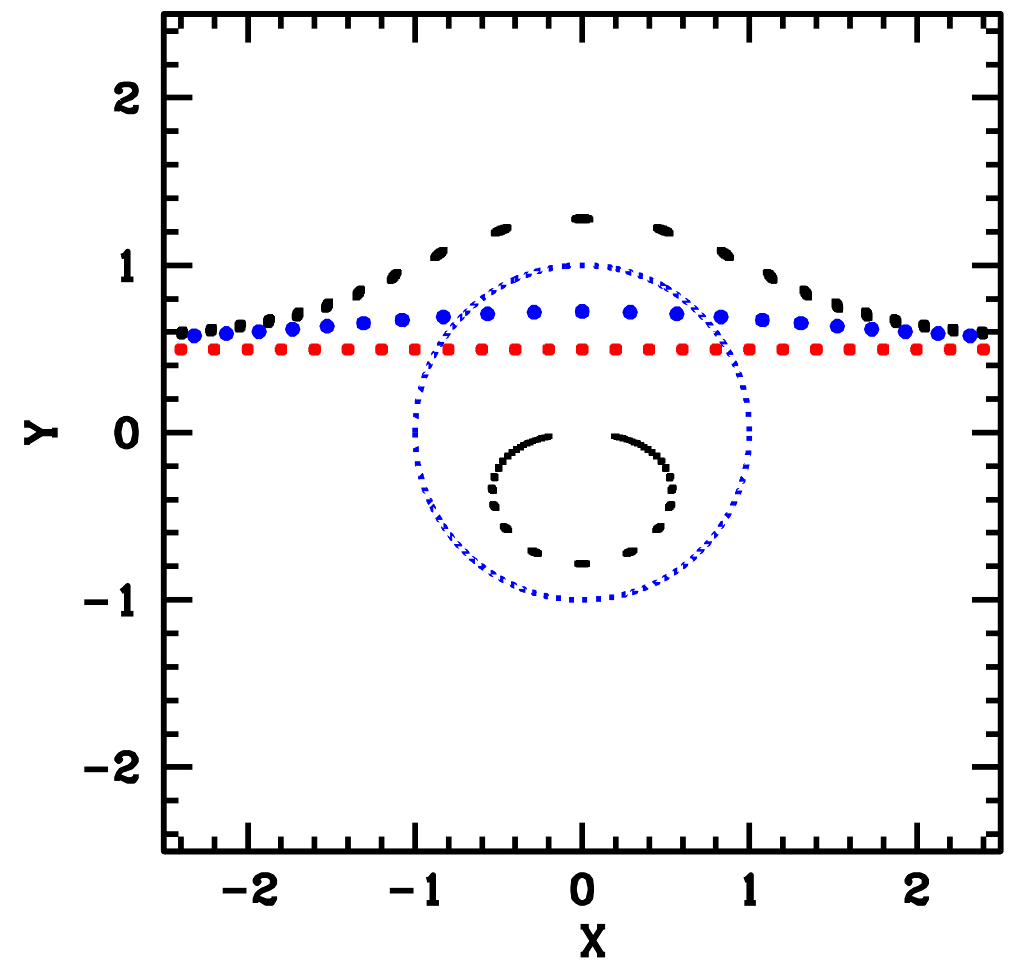
So the mass estimates from timescales are only statistical in nature.



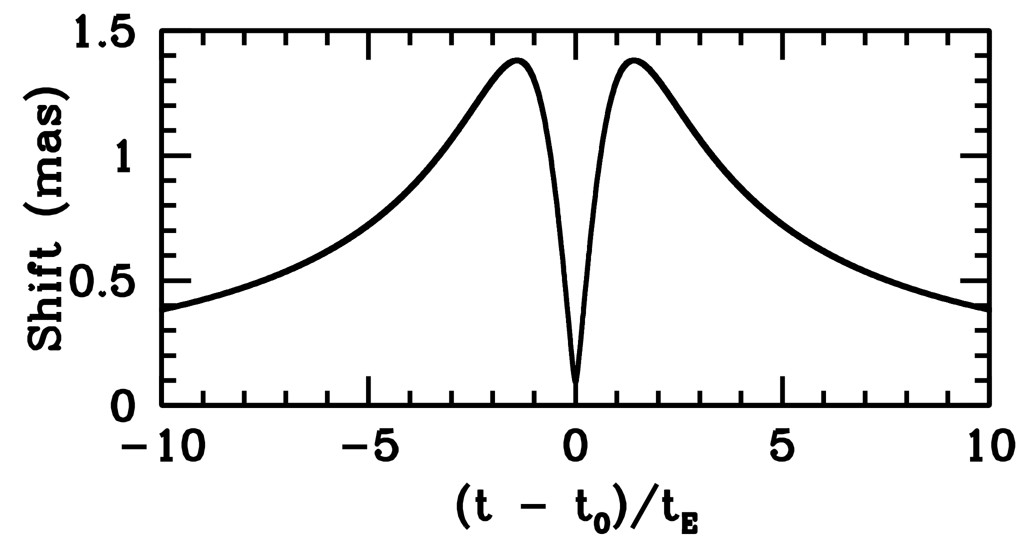
Microlensing can break the degeneracy

$A = [u^2+2]/[u(u^2+4)]$
Amplification is a pure function of u

The astrometric shift:
$\delta = u\,\Theta_E/[u^2+2]$
Thus δ is a direct measure of Θ_E

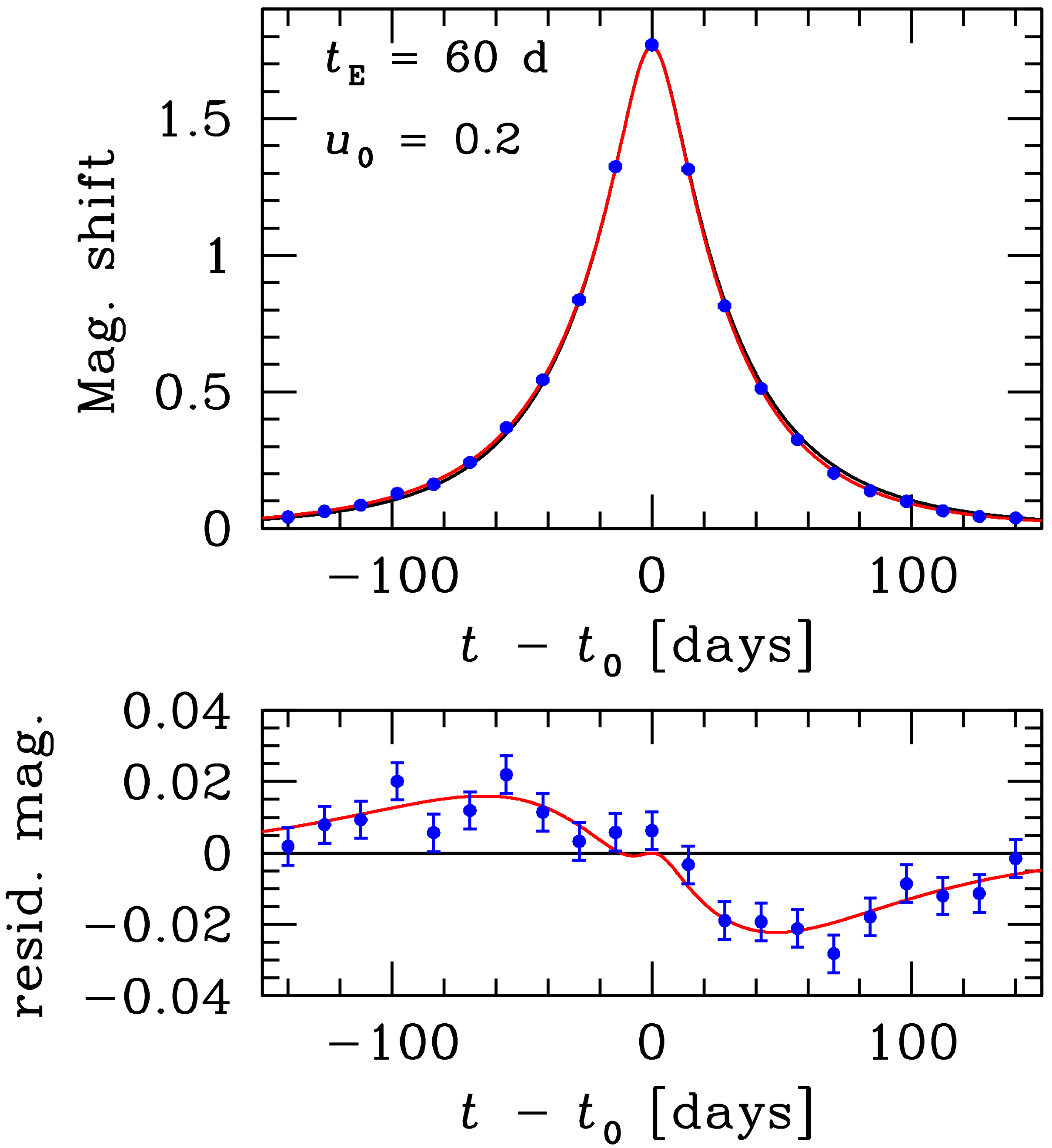


$\Theta_E = R_E/D_L = [(4GM/C^2)\, D_{LS}/(D_L\, D_S)]^{0.5}$



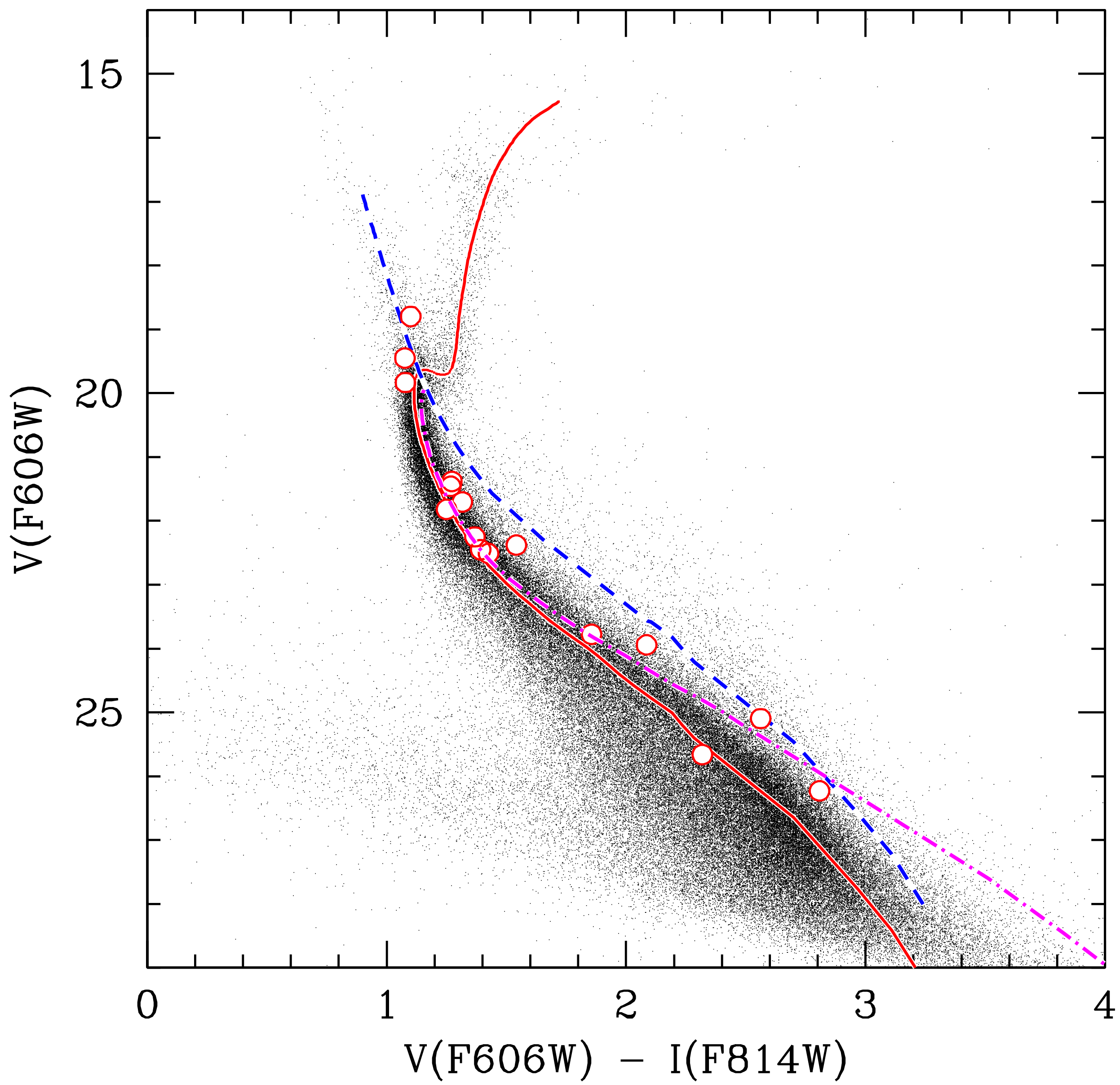
- **Astrometric shift, combined with the distances provide an unambiguous measurement of the mass of the lens.**

Distance to the Lens



- Earth's motion around the Sun introduces a distortion on the microlensing light curve.
- Such "parallax" measurements provide an estimate of the distance to the lens.
- Ground-based follow-up observations can be used for parallax measurements.

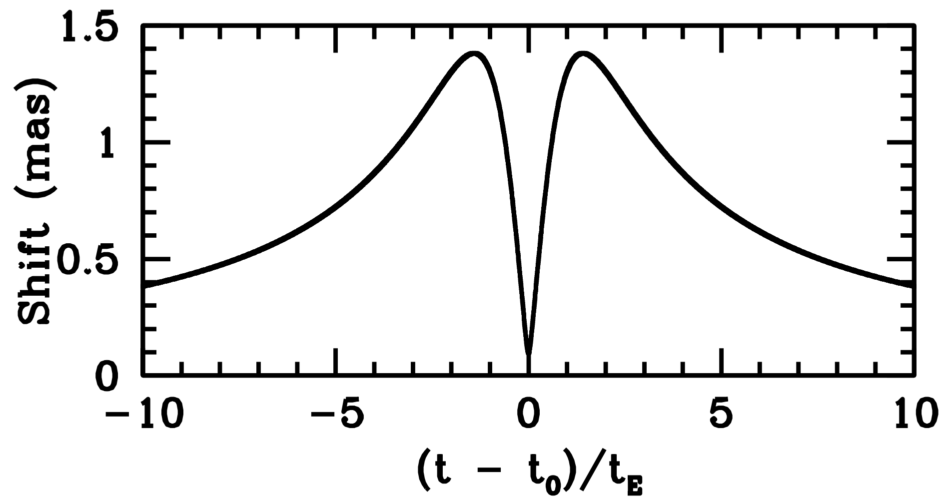
Distance to the Source

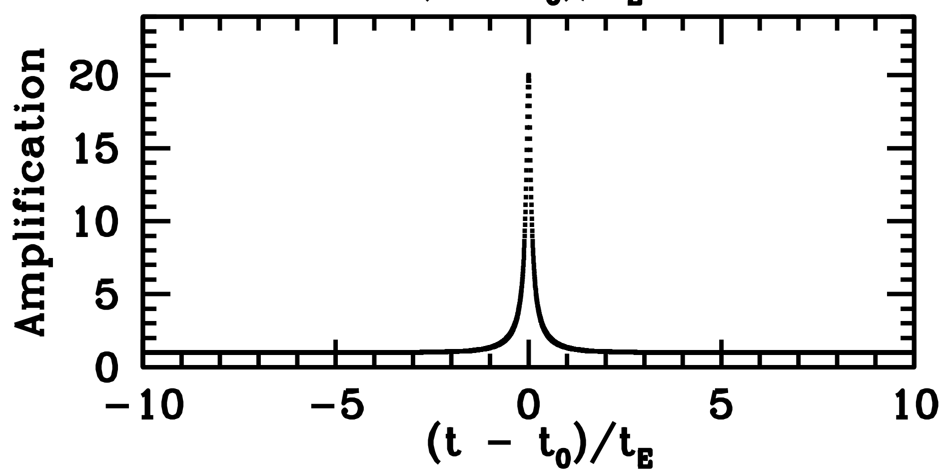


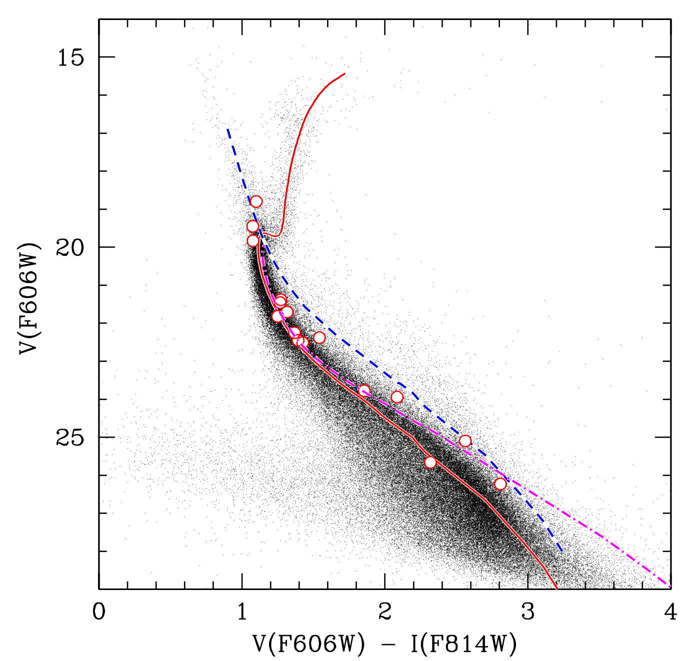
Sahu et al. 2006, Nature, 443, 534

- For microlensing events observed towards the Galactic bulge, >95% of the sources lie within the bulge.
- The observed CMD is often useful in confirming that the source is indeed in the bulge.
- Spectroscopic observations can also be used for spectral type/distance measurements.

Physical parameters from astrometric microlensing







$\Theta_E = R_E/D_L = [(4GM/C^2)\ D_{LS}/(D_L\ D_S)]^{0.5}$

- δ, A ⇒ Θ_E
- Parallax signal ⇒ D_L
- CMD ⇒ D_S

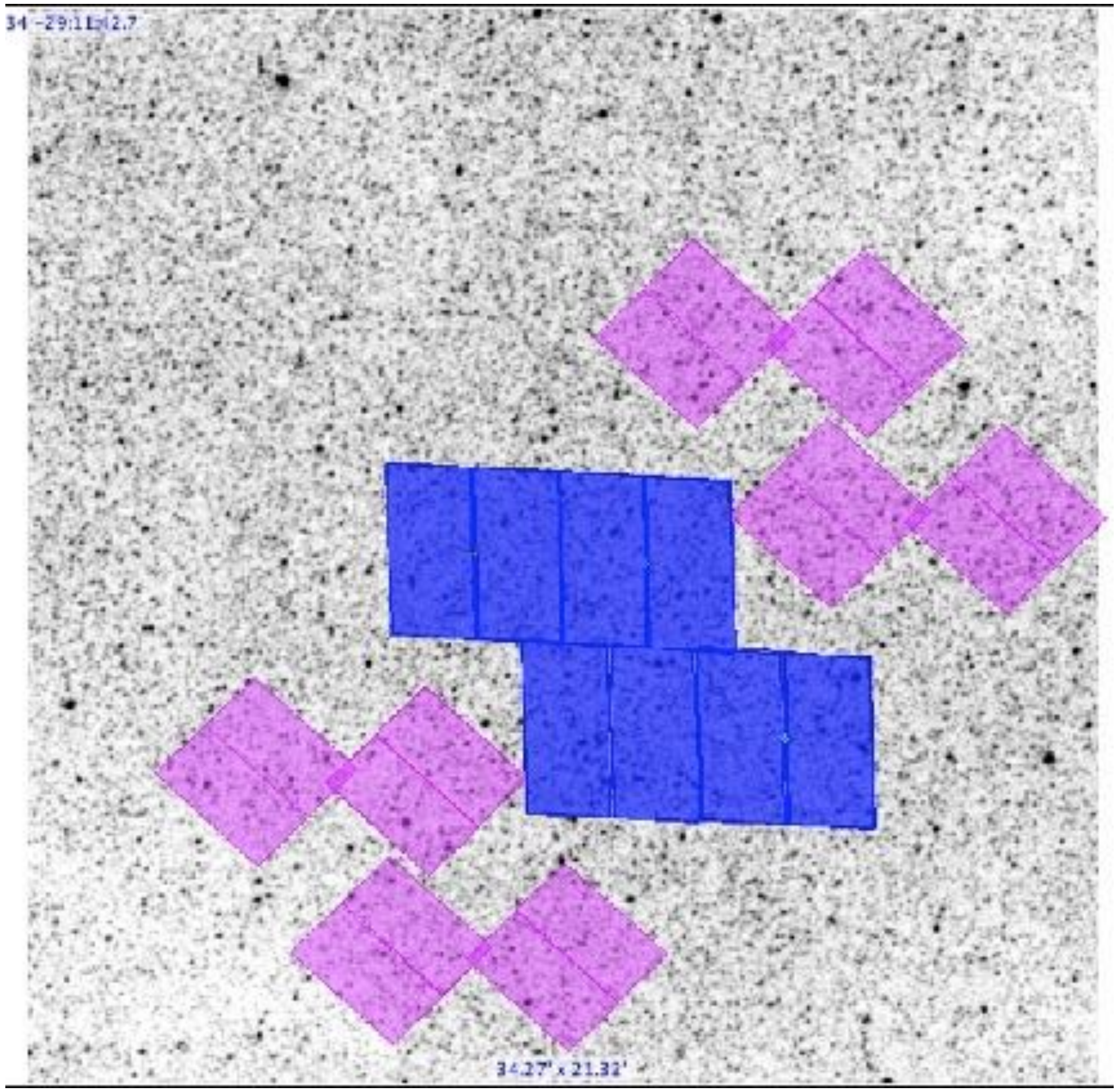
➡ Mass of the Lens

- T_E ⇒ V_L
- Unequivocal detection of BHs with measurements of:
  - the mass,
  - the distance and
  - the velocity

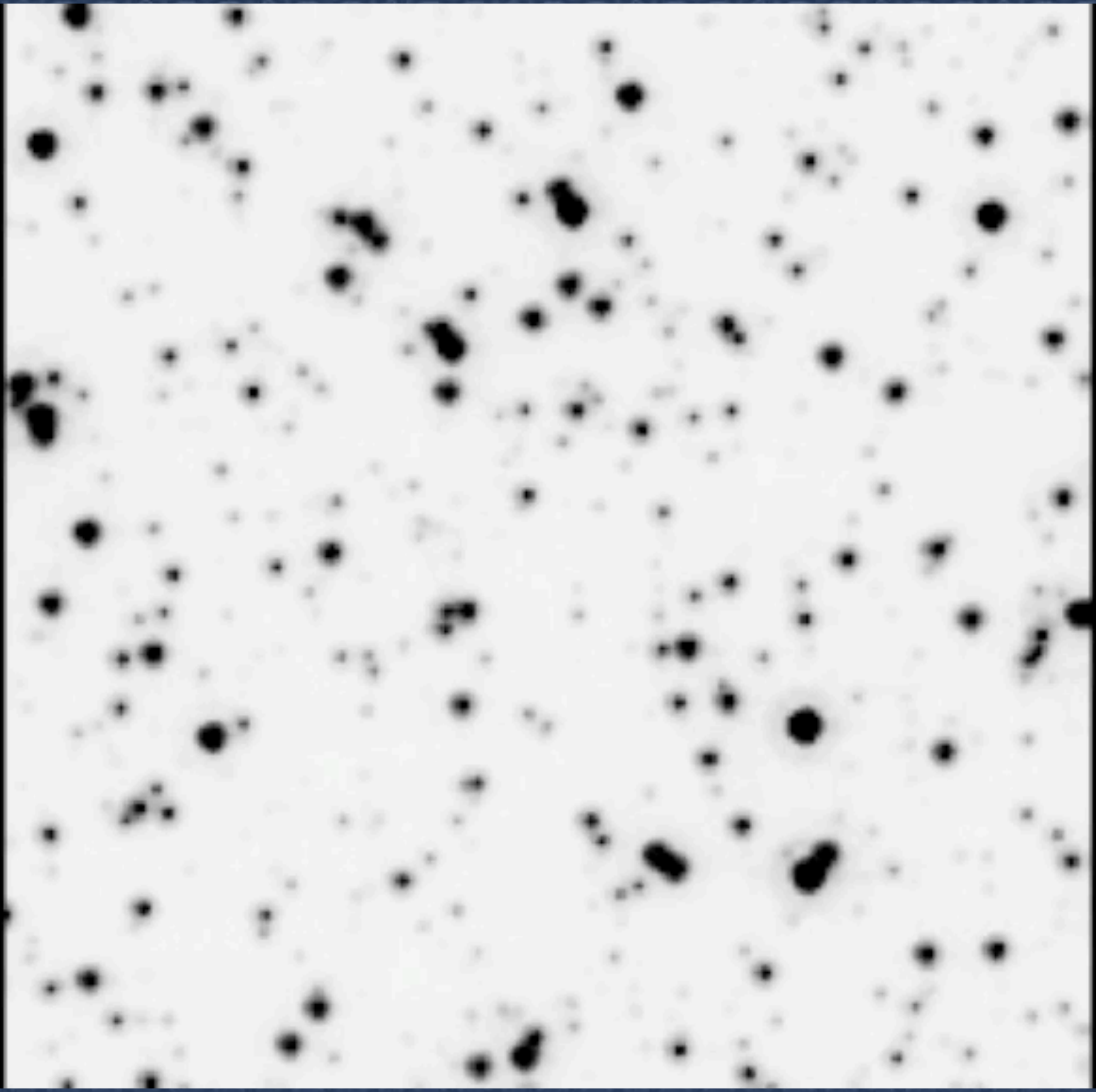
from a single technique.

II. Detecting and Measuring the Masses of Stellar Remnants (GO-12586, PI: Sahu)

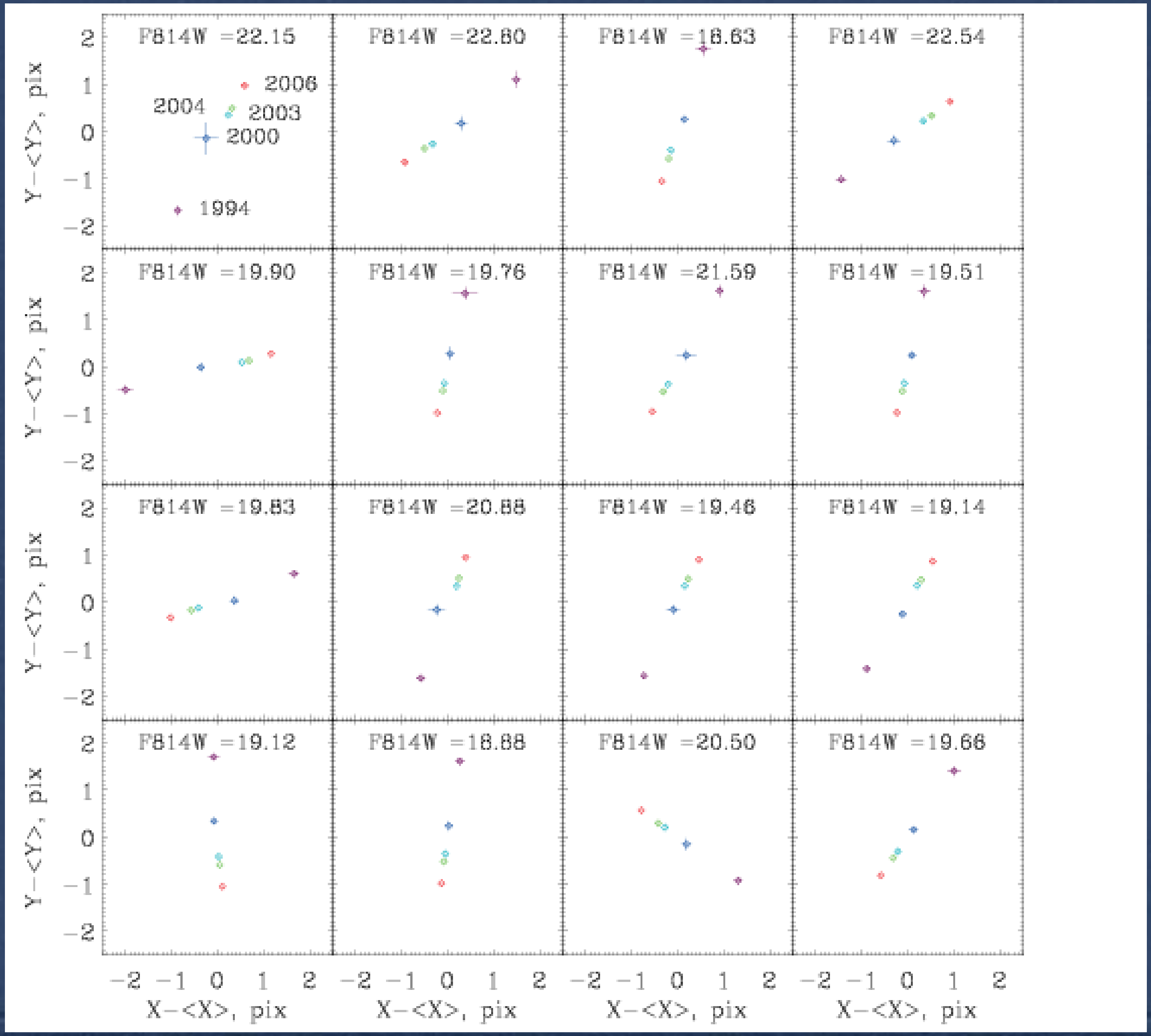
- **Fields/ Targets**
  - 4 ACS fields, each with ~180,000 stars
  - 8 WFC3/UVIS fields, each with ~120,000 stars
  - **Total of 1.7 million stars, 50% with astrometric measurements**
- **Observing Cadence**
  - One visit every 2 weeks over two 4-month windows
  - 64 visits per year, for 3 years
  - Optimized for long-duration events.



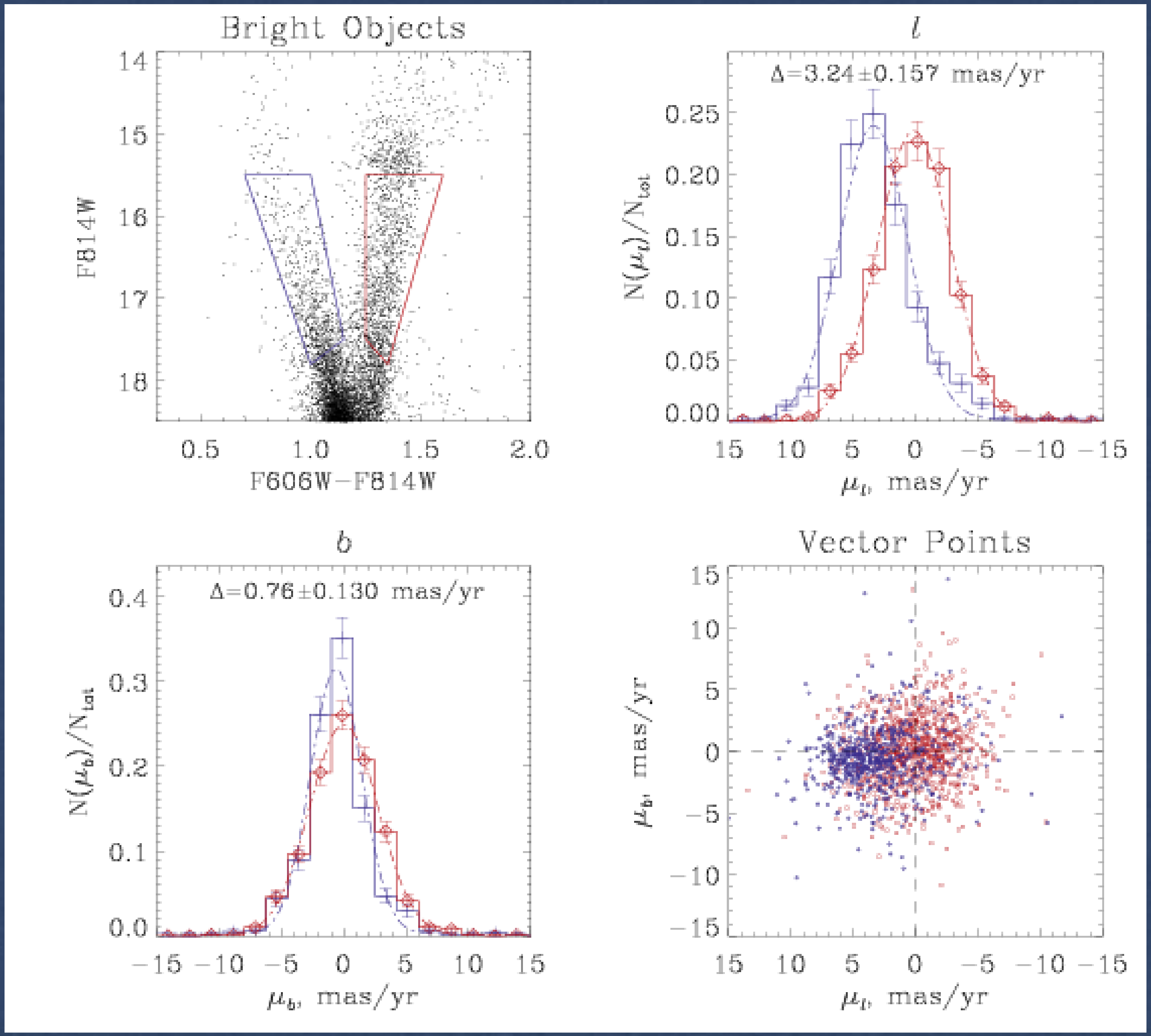
This provides a few more epochs for PM measurements.



Example PM Measurements (Clarkson, Sahu et al. 2008)

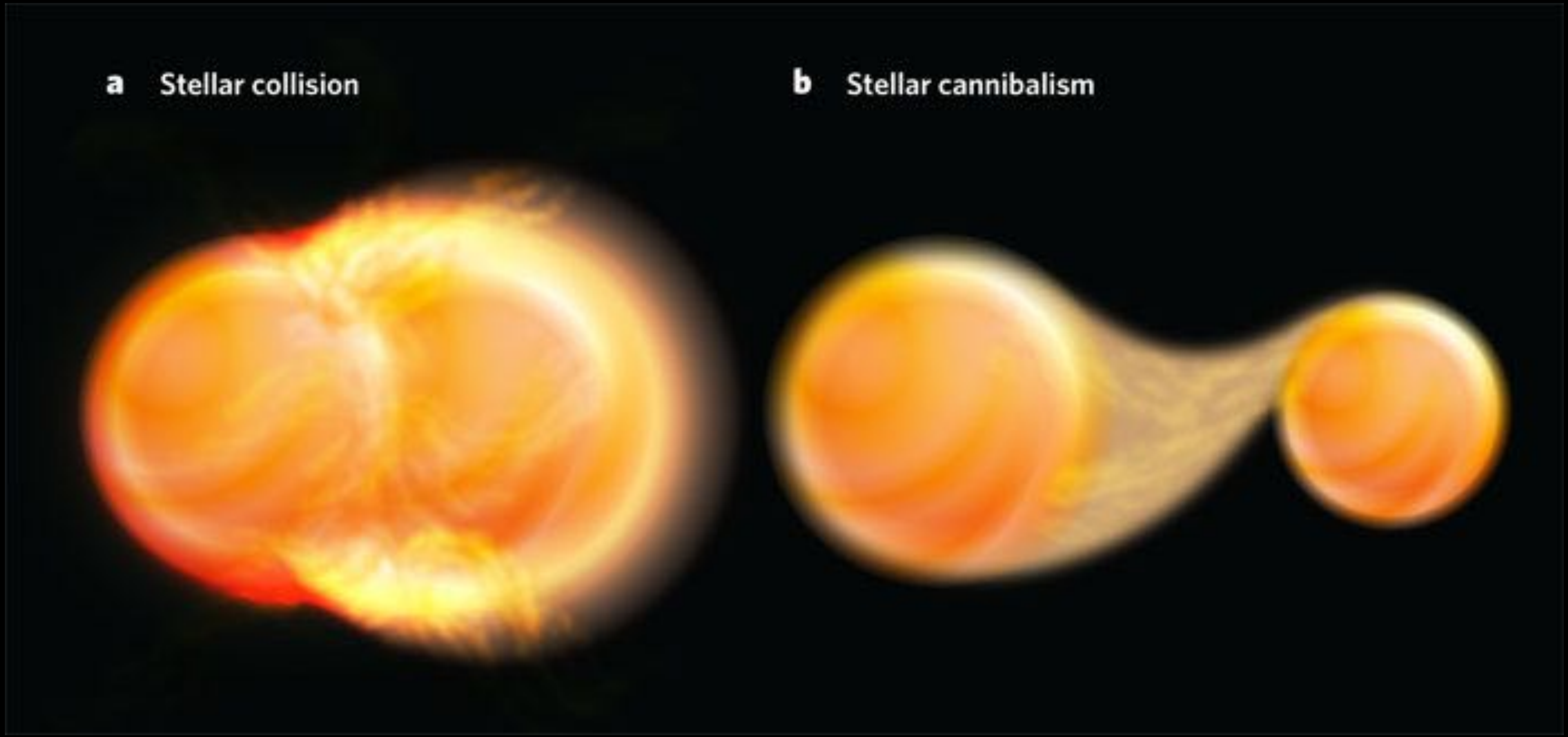


PMs of Disk and Bulge Components

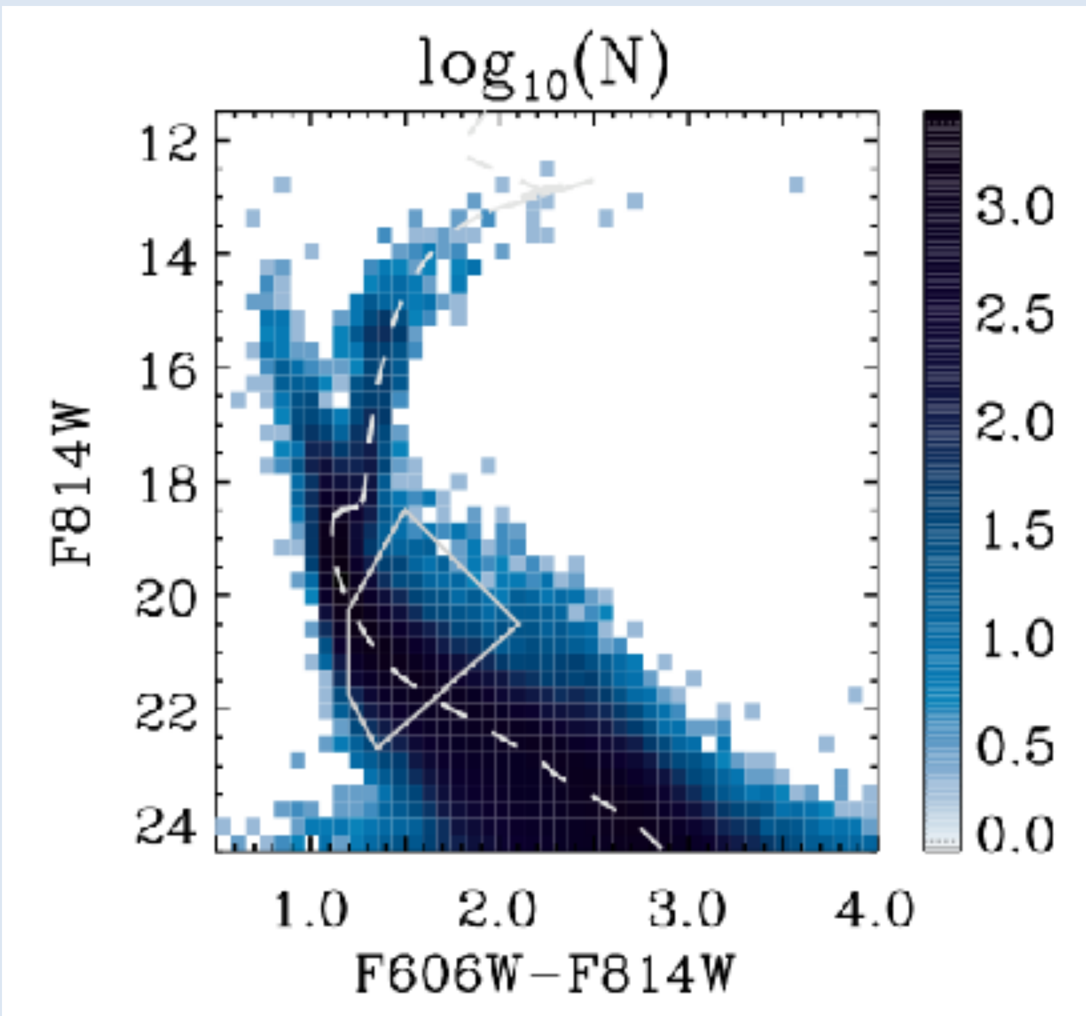


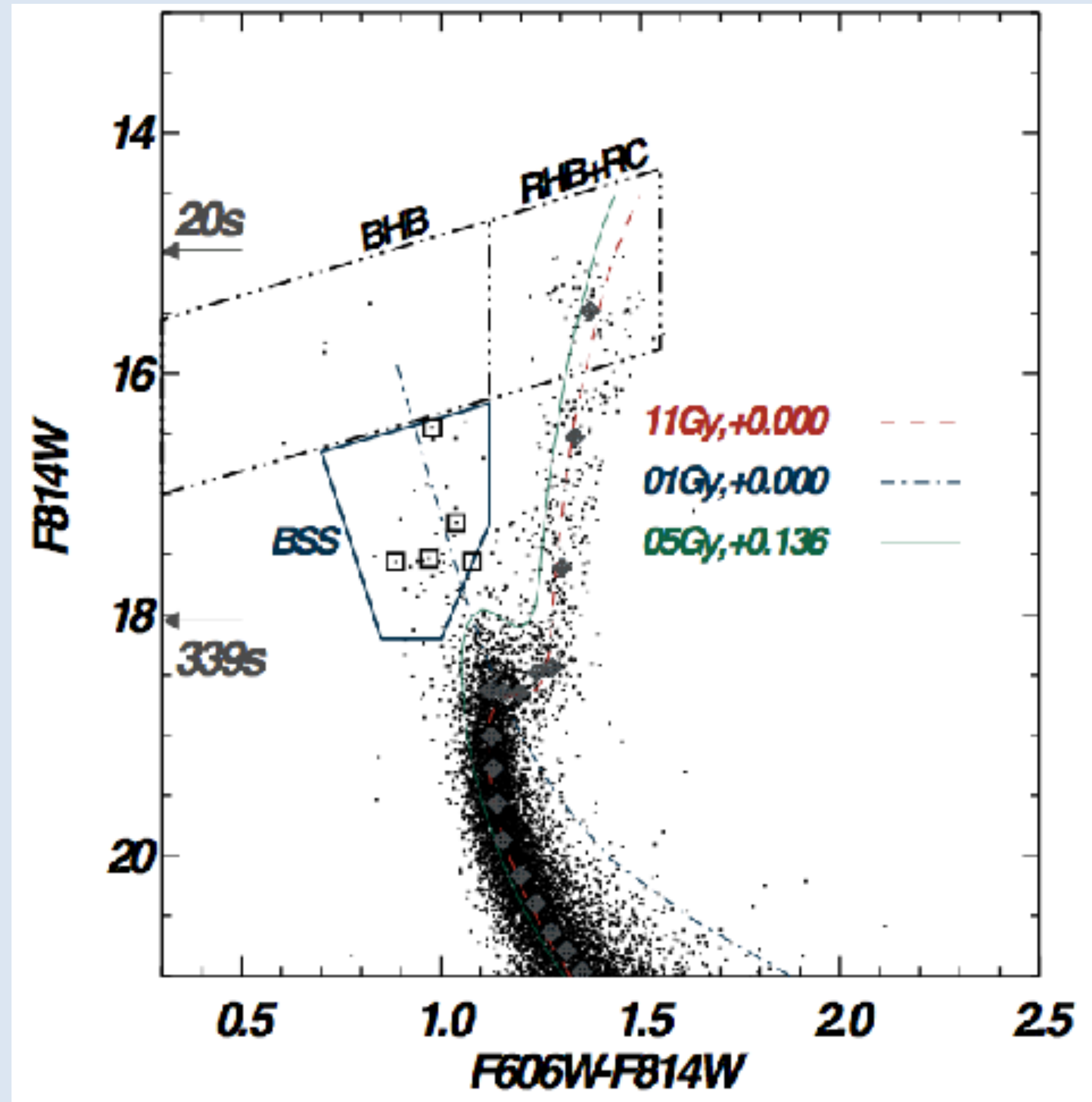
Discovery of Blue Straggler Stars in the Bulge
(Clarkson, Sahu et al. 2011)

- Blue Straggler Stars are old stars made more luminous and hotter by mass transfer
  - In brightness and color, they mimic the appearance of much younger stars
  - We don't yet know the full story for how these objects form



Blue Stragglers in the Milky Way Bulge



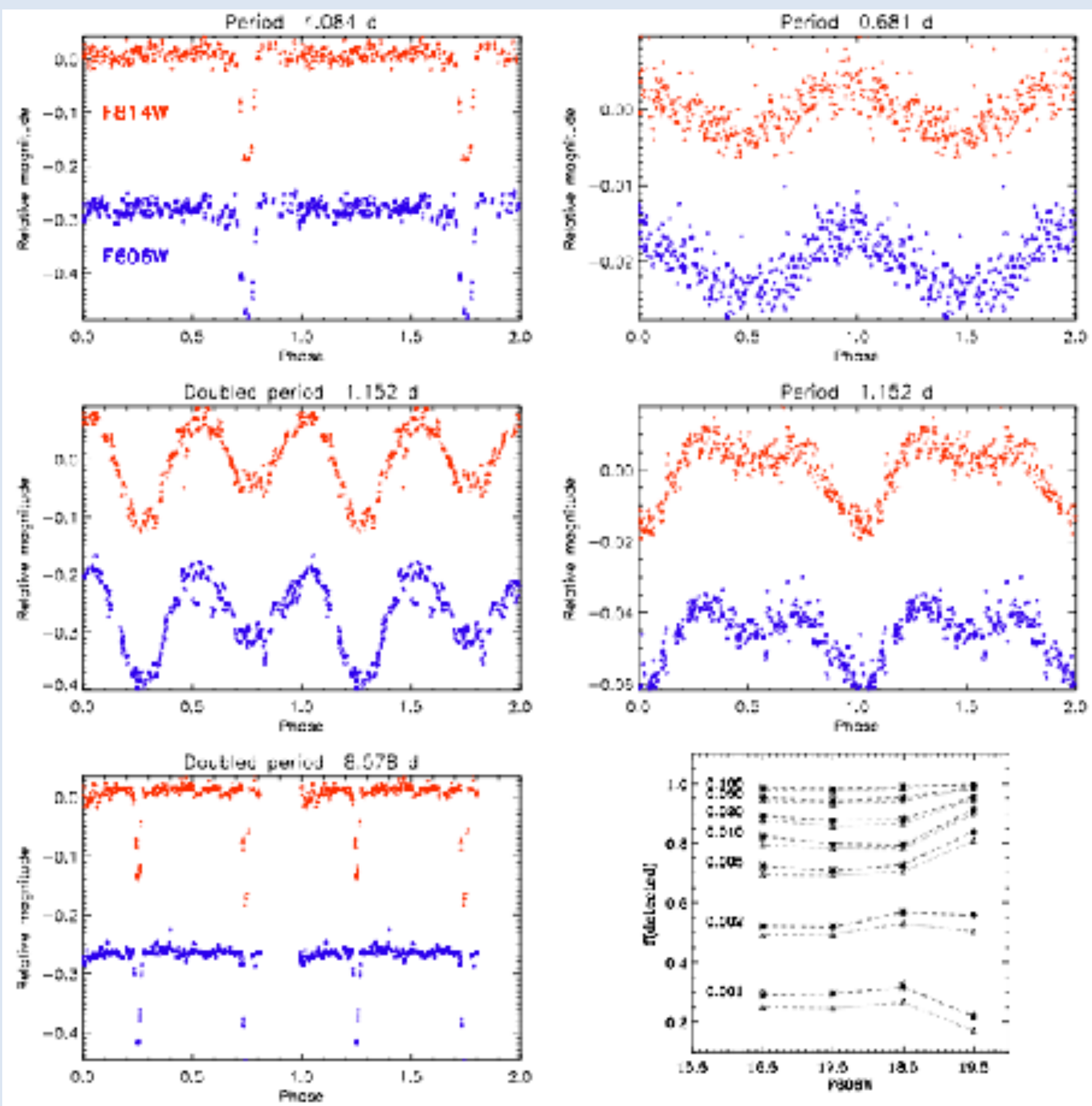


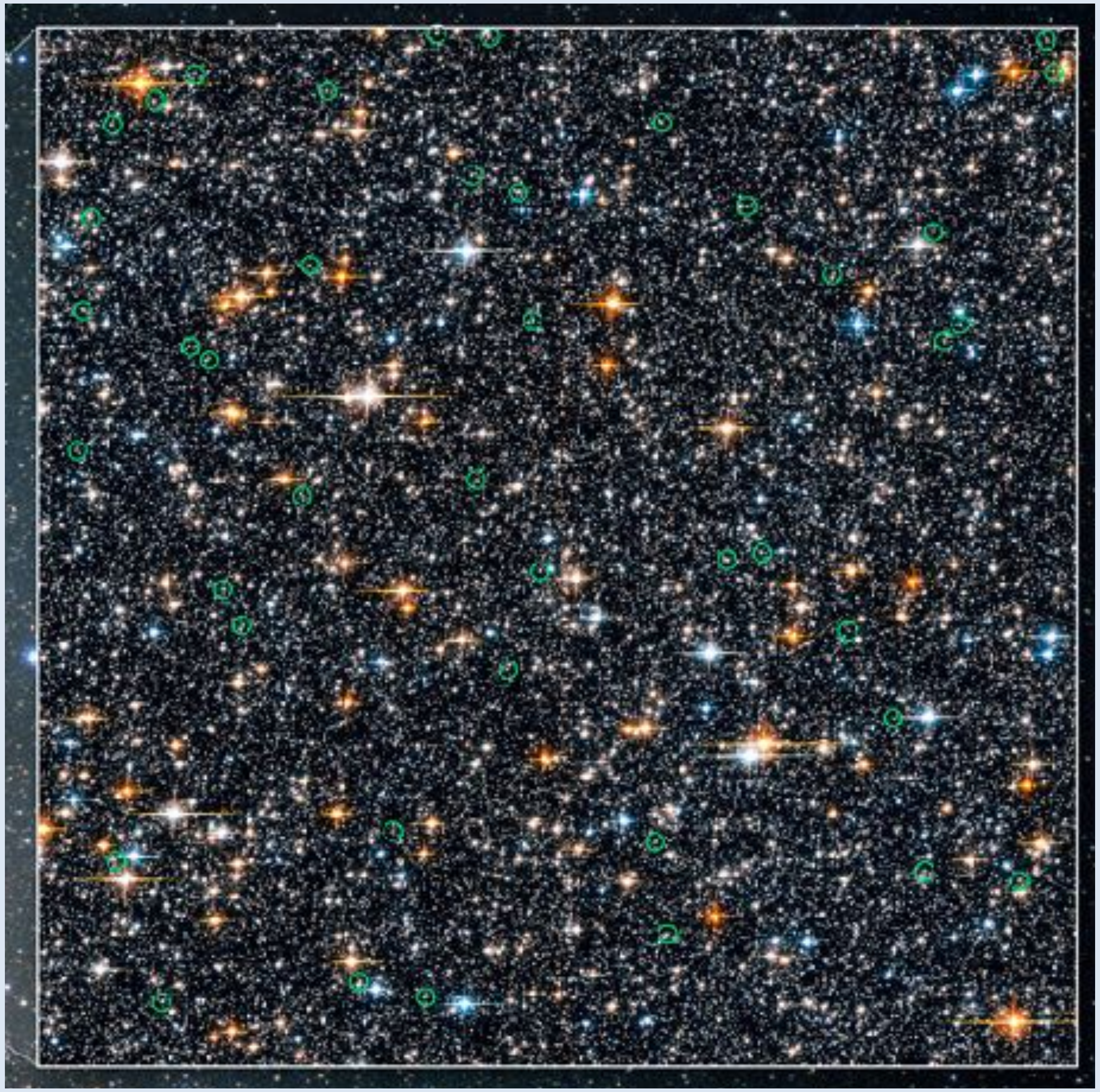
•Result: 42 objects with bulge kinematics in the BSS region of the CMD

CMD from bulge-selected stars
Clarkson et al. 2011 ApJ in press

Photometric variability

•Some bulge BSS should be associated with present-day close binaries

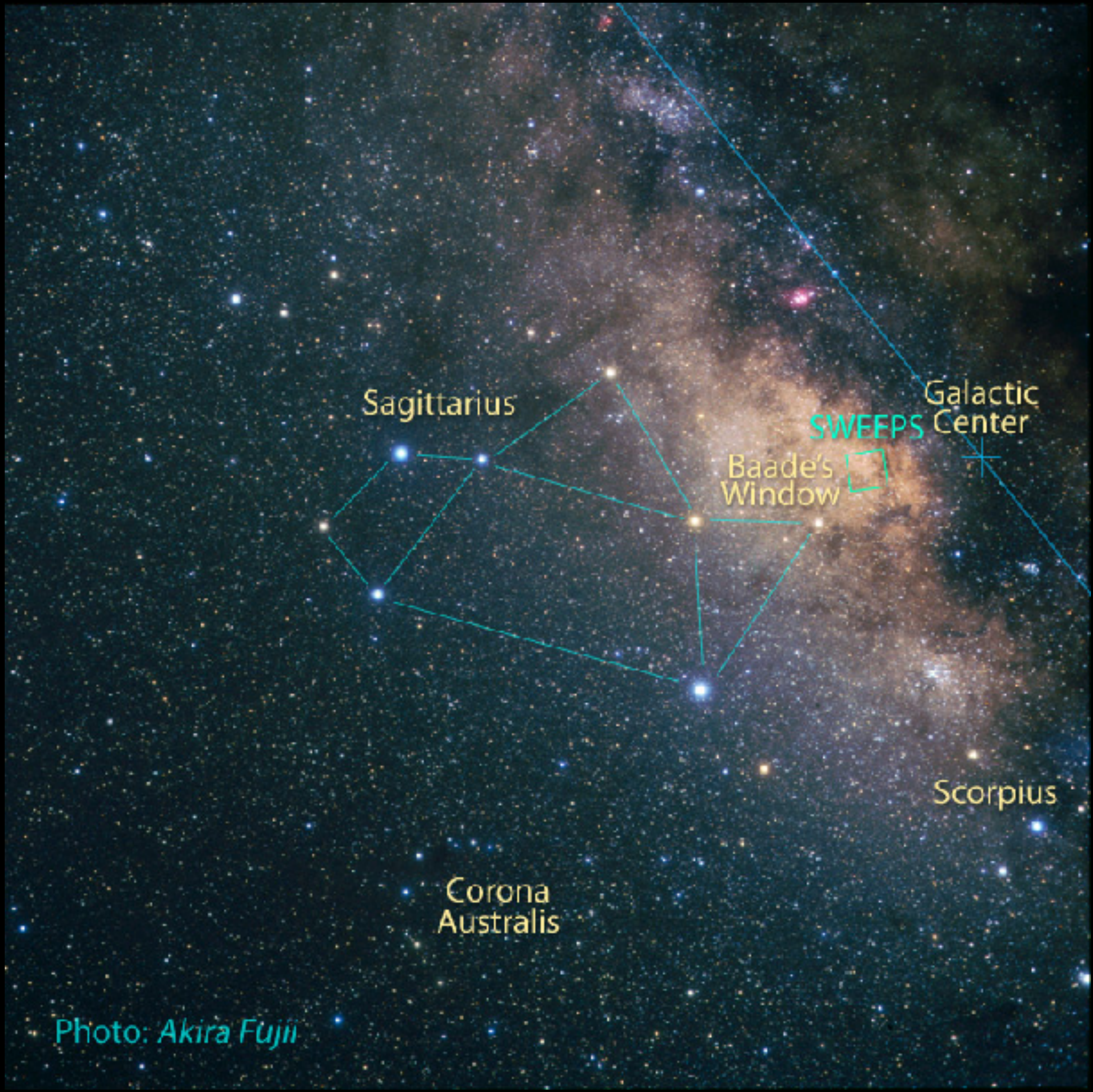




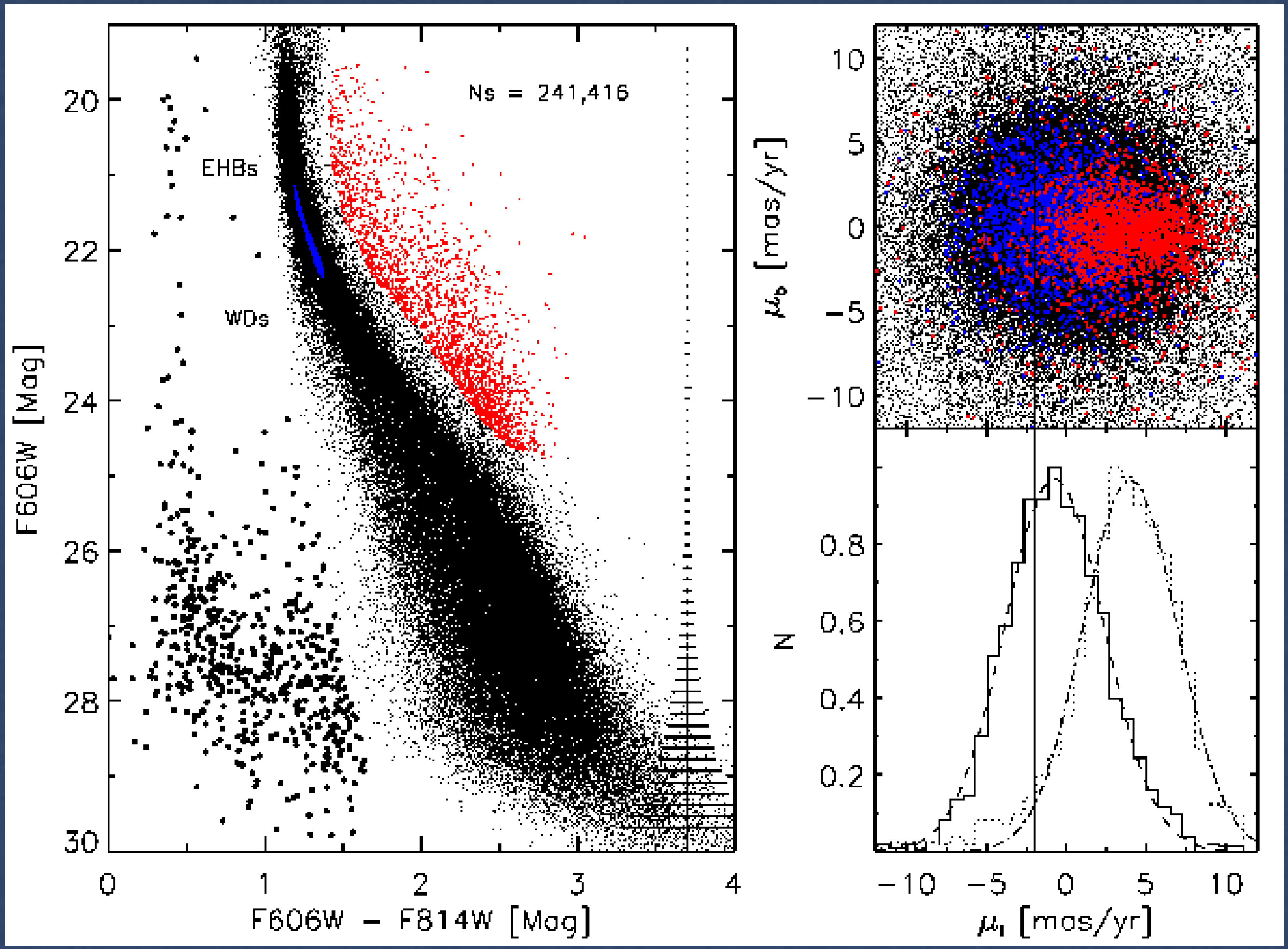
Locations of the Blue Straggler Stars

What does this tell us about the Bulge?

- Of the bulge stars with brightness and color of young stars, most are actually old blue stragglers.
- This implies that, within this region of the Milky Way bulge, fewer than about 3.4 percent of the stars are relatively young (<5 billion years old).

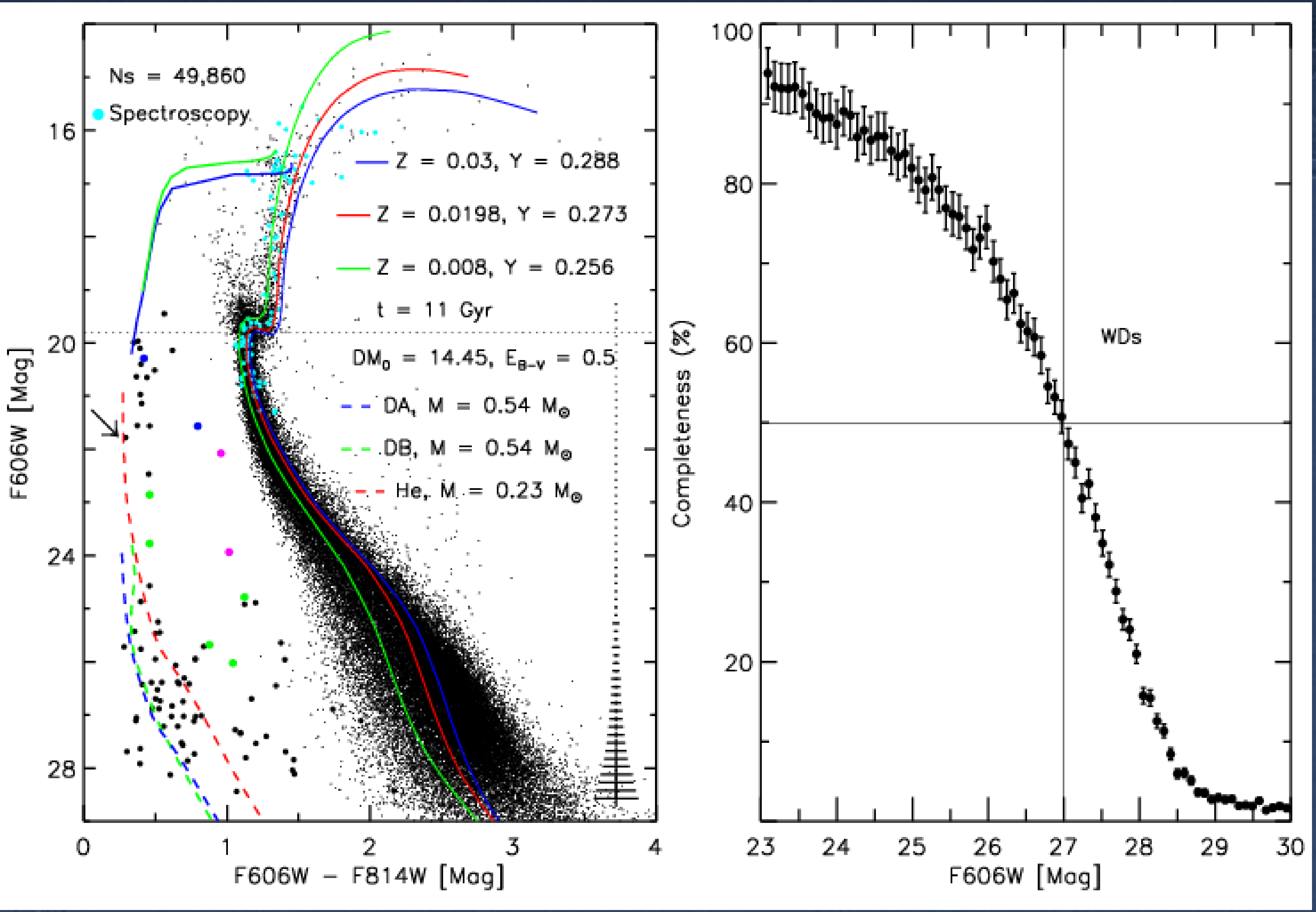


Detection of WD population in the Bulge
(Calamida, Sahu et al. 2015).



PMs were measured with an accuracy of ≈ 0.1 $masyr^{-1}$ (≈ 4 kms^{-1}) at V≈ 25.5 mag, and ≈ 0.5 mas yr^{-1} at V≈ 28 mag, which allowed us to separate disk and bulge stars and obtain a clean bulge color-magnitude diagram.

We identified for the first time a white dwarf (WD) cooling sequence in the Galactic bulge.



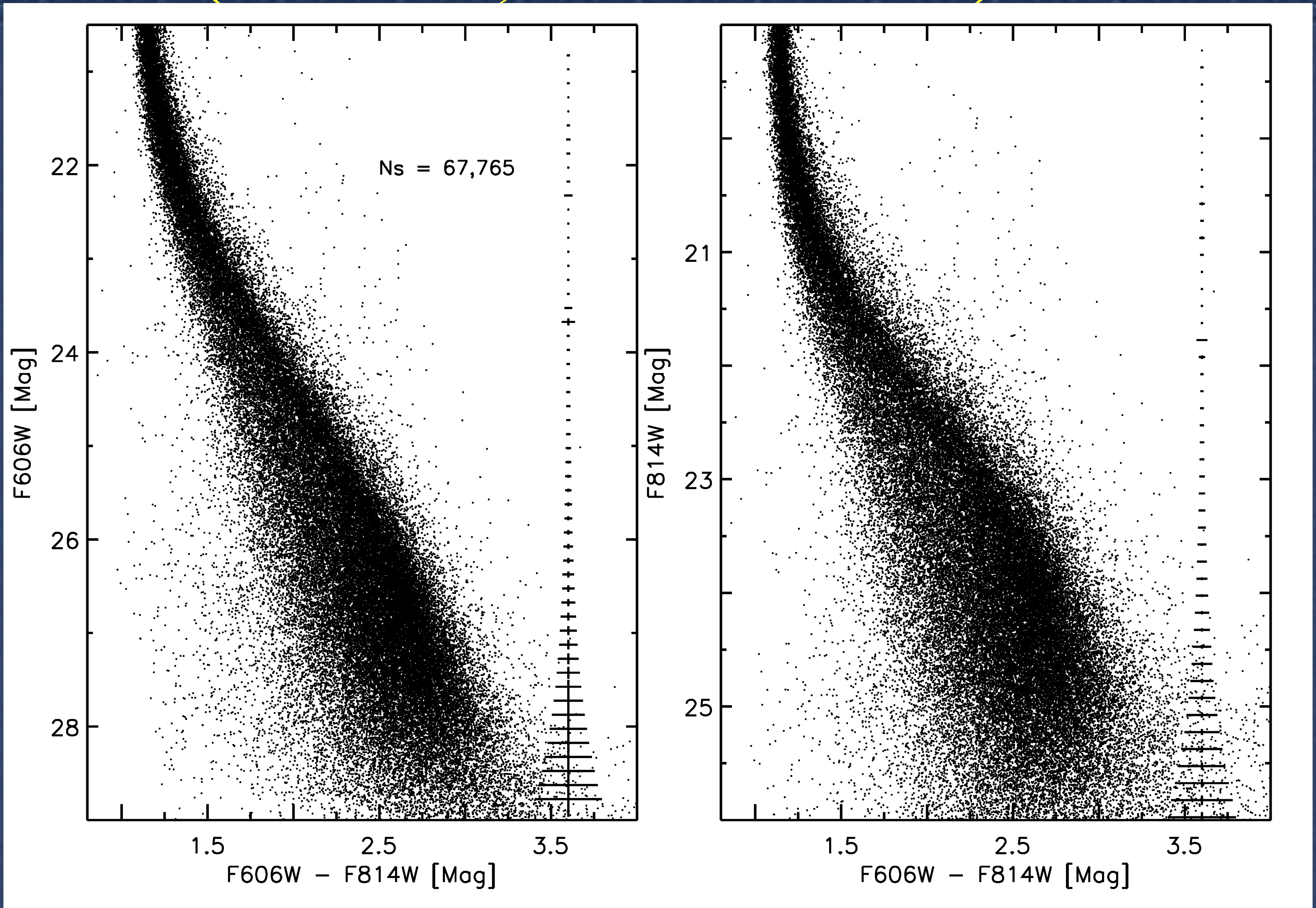
About 30% of the WDs are systematically redder than the cooling tracks for CO-core WDs.

This evidence would suggest the presence of a significant number of He-core, low-mass WDs and WD-main sequence binaries in the bulge.

This hypothesis is further supported by the finding of two dwarf novae in outburst, two short-period (P 1 d) ellipsoidal variables, and a few candidate cataclysmic variables in the same field.

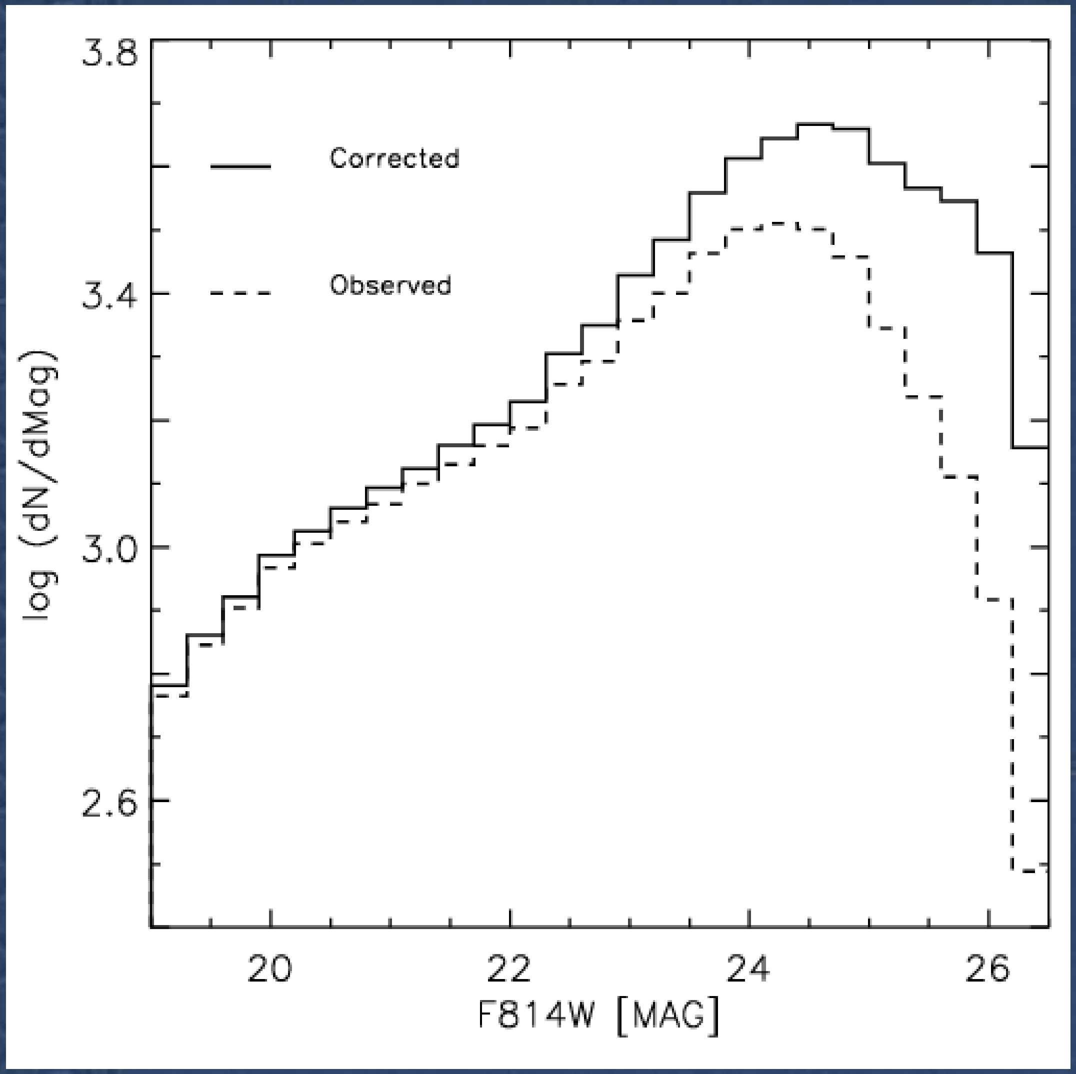
Mass Function of the Pure Bulge Population

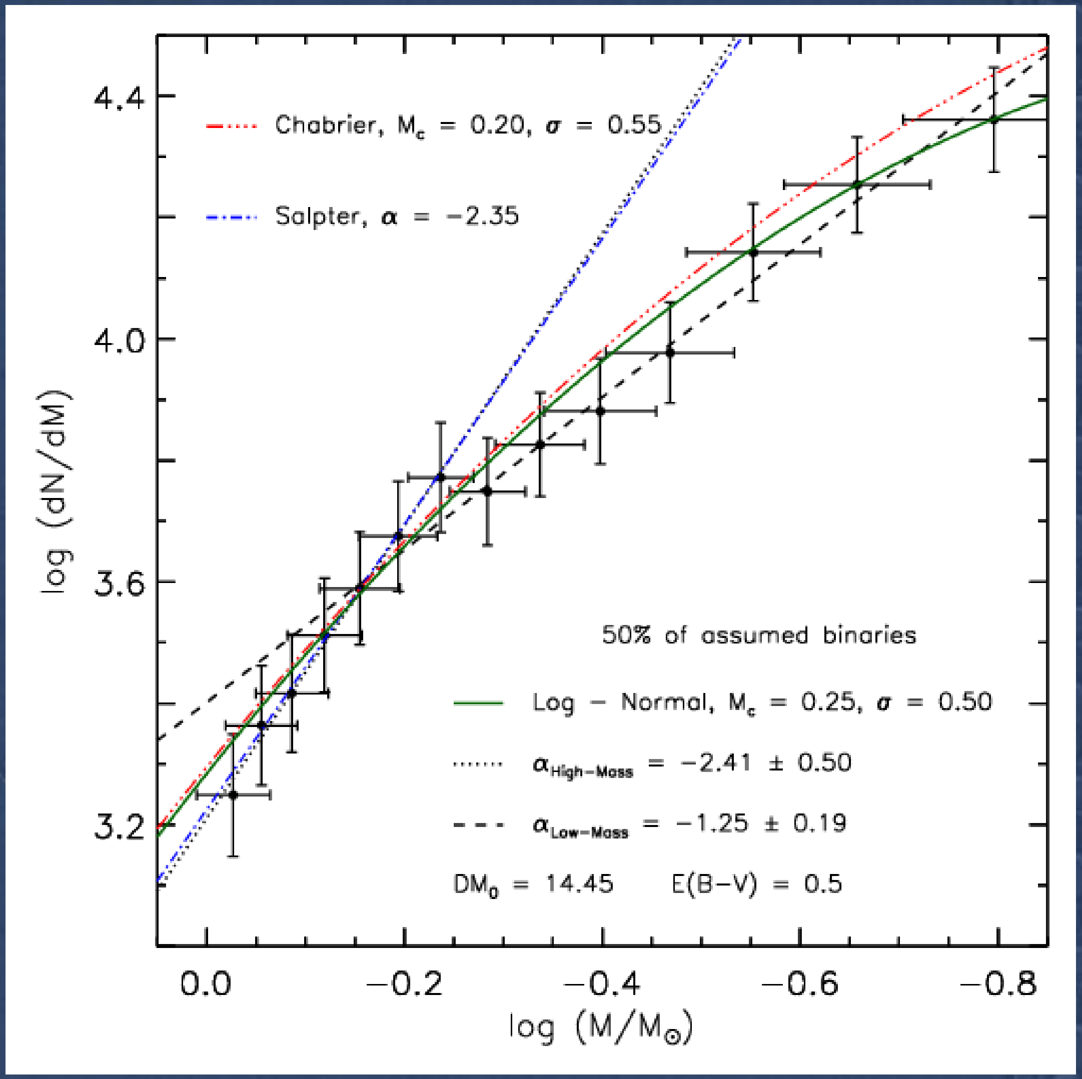
(Calamida, Sahu et al. 2016).



We have derived the Galactic bulge initial mass function of the SWEEPS field down to 0.15 M⊙.

Mass Function of the Pure Bulge Population
(Calamida, Sahu et al. 2016).





In the high-mass range, our derived mass function agrees well with the mass function derived for other regions of the bulge. In the low-mass range however, our mass function is slightly shallower, which suggests that separating the disk and bulge components is particularly important in the low- mass range.

PM measurements with WFIRST

WFIRST will measure PMs of ~150 million stars of all spectral types, with an accuracy of ~0.3 mas/yr. They can be used for:

- Bulge-disk separation, which allows study of pure bulge population.
- Study of present-day internal kinematics of the bulge.
- Kinematics of the microlensed sources.
- Confirming that microlensed sources are indeed in the bulge.
- Initial guesses on timescales of lens-source separation.
- Combining with RV to get 3-D kinematics of the bulge.
- Many follow-up studies.

PM Measurements with WFIRST

- **GAIA's sensitivity in the crowded bulge field is low.**
- **For PM and BH studies: it is best if a small fraction (~1 hr observation every ~5 to 10 days, which would require less than 1 day per year) of the microlensing campaign can be extended to the entire lifetime.**