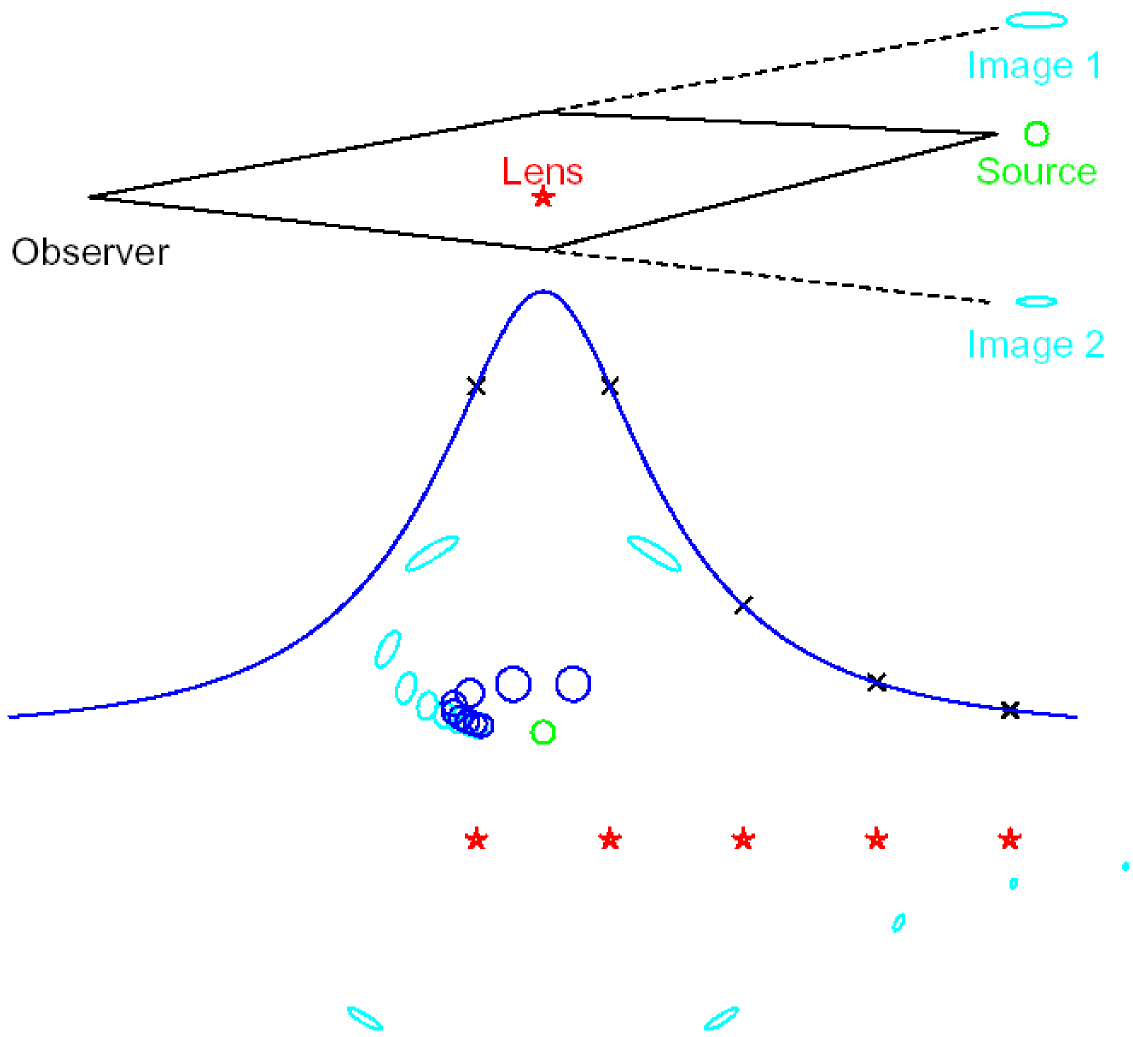
Microlensing VII:
Applications to Astrophysics
Andy Gould (Ohio State)



Variable Stars

- Deep connection to microlensing

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  - Many thought: insurmountable contaminant

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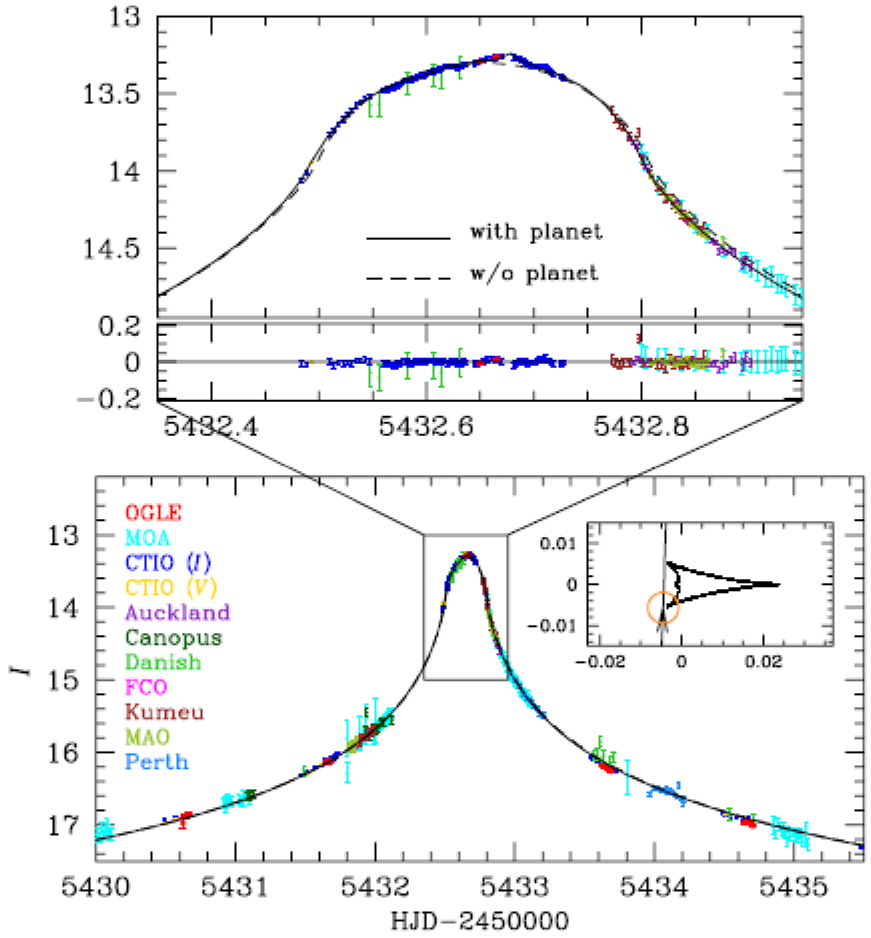
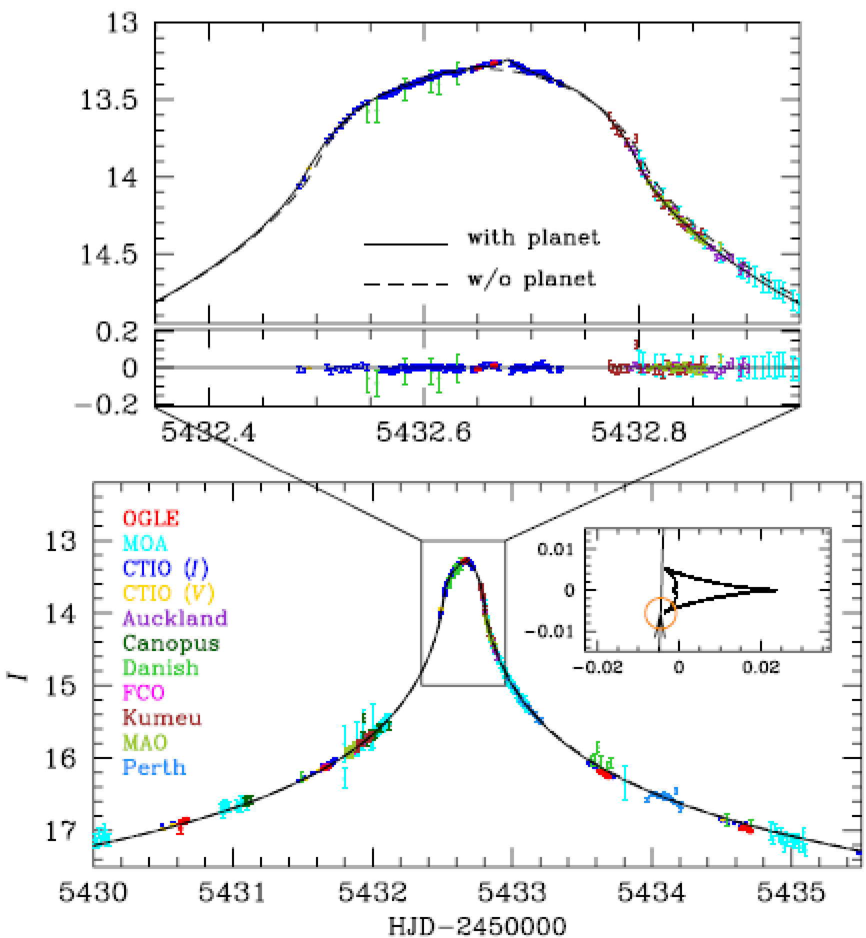
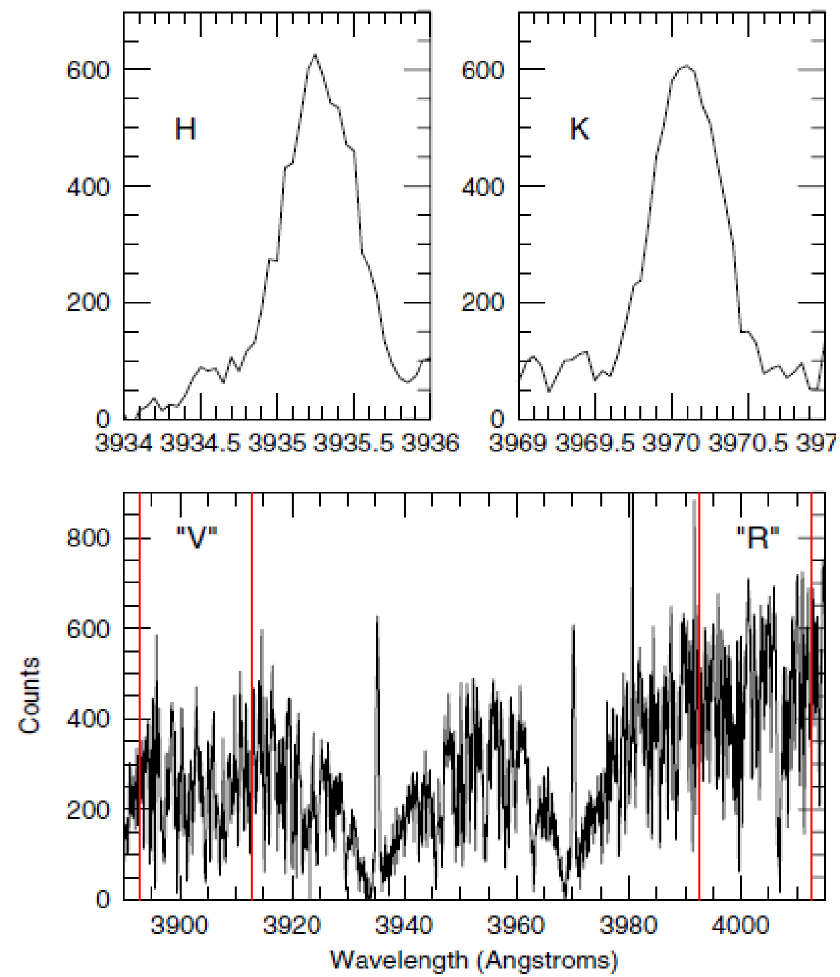
MOA-2010-BLG-523: "Failed" Planet



Gould, Yee, et al. 2013, ApJ, 763, 141

MOA-2010-BLG-523: “Failed” Planet





Gould, Yee, et al. 2013, ApJ, 763, 141

Variable Stars

- Deep connection to microlensing
  - Many thought: insurmountable contaminant
  - Main driver for Polish OGLE survey

P. PIETRUKOWICZ[1], A. UDALSKI[1], I. SOSZYŃSKI[1], D. M. NATAF[2], Ł. WYRZYKOWSKI[1,3], R. POLESKI[1], S. KOZŁOWSKI[1], M. K. SZYMAŃSKI[1], M. KUBIAK[1], G. PIETRZYŃSKI[1,4], AND K. ULACZYK[1]
[1] Warsaw University Observatory, Al. Ujazdowskie 4, 00-478 Warszawa, Poland
[2] Department of Astronomy, Ohio State University, 140 West 18th Avenue, Columbus, OH 43210, USA

Variable Stars

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  - Main driver for Polish OGLE survey
- RR Lyrae Stars

THE OPTICAL GRAVITATIONAL LENSING EXPERIMENT: ANALYSIS OF THE BULGE RR LYRAE POPULATION FROM THE OGLE-III DATA

P. PIETRUKOWICZ[1], A. UDALSKI[1], I. SOSZYŃSKI[1], D. M. NATAF[2], Ł. WYRZYKOWSKI[1,3], R. POLESKI[1], S. KOZŁOWSKI[1], M. K. SZYMAŃSKI[1], M. KUBIAK[1], G. PIETRZYŃSKI[1,4], AND K. ULACZYK[1]
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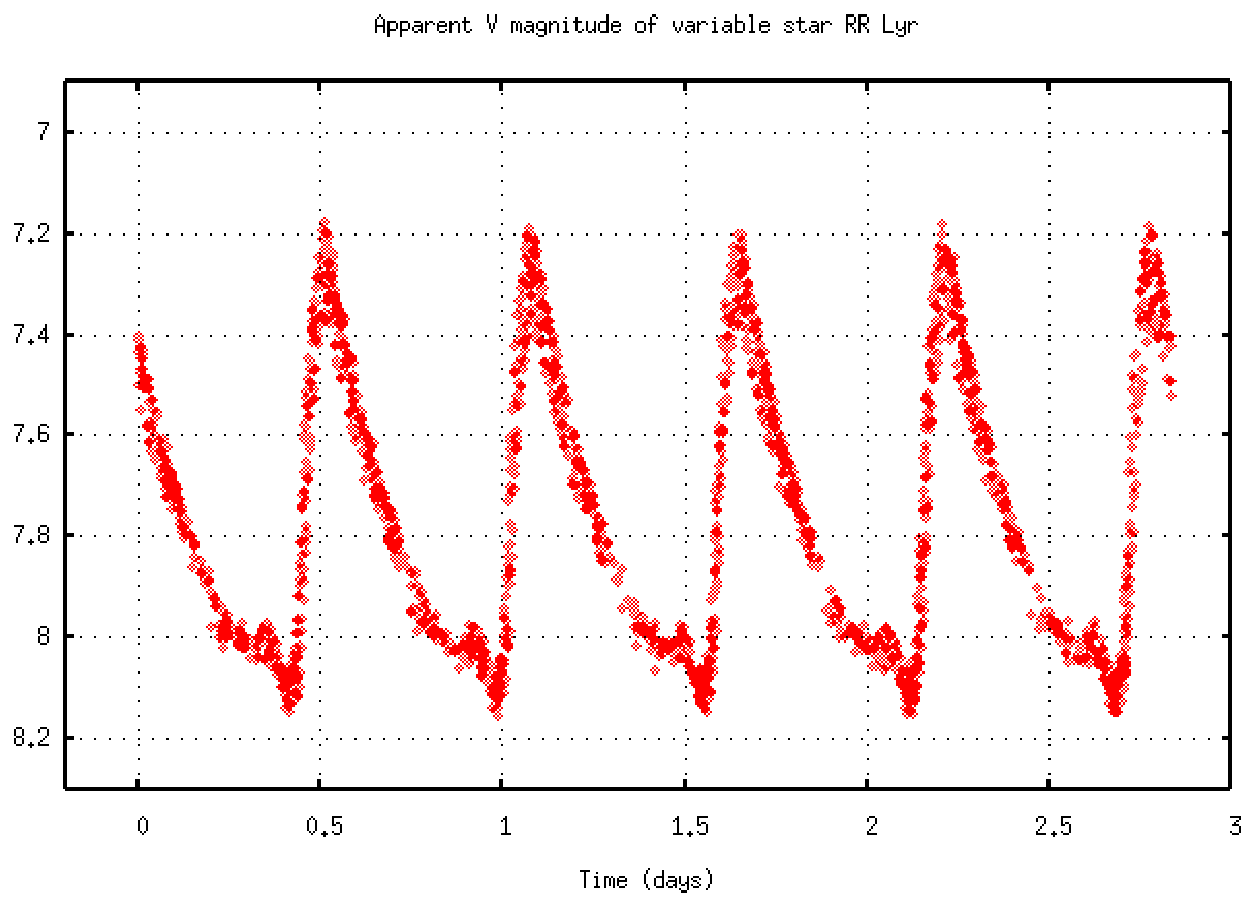
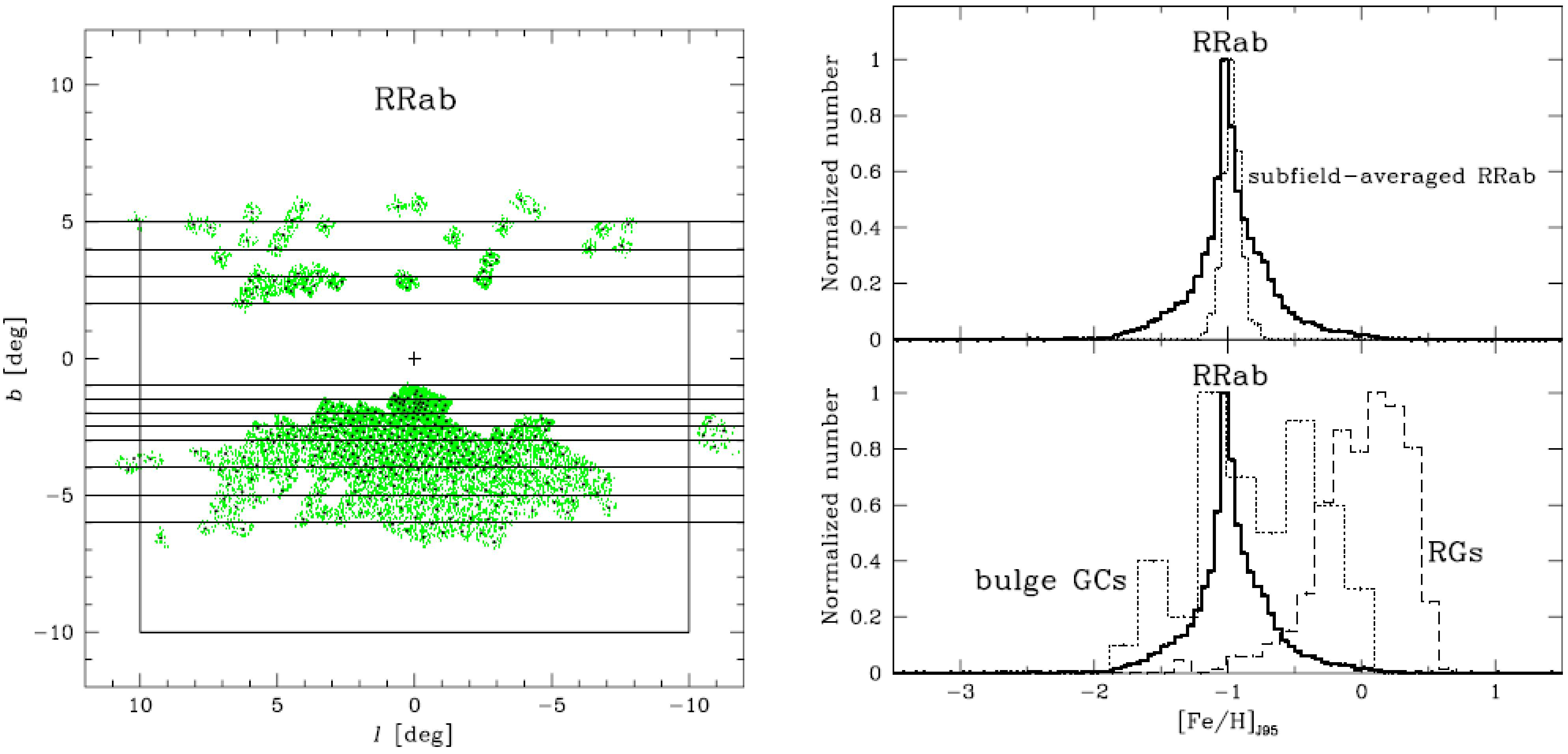
RR Lyra

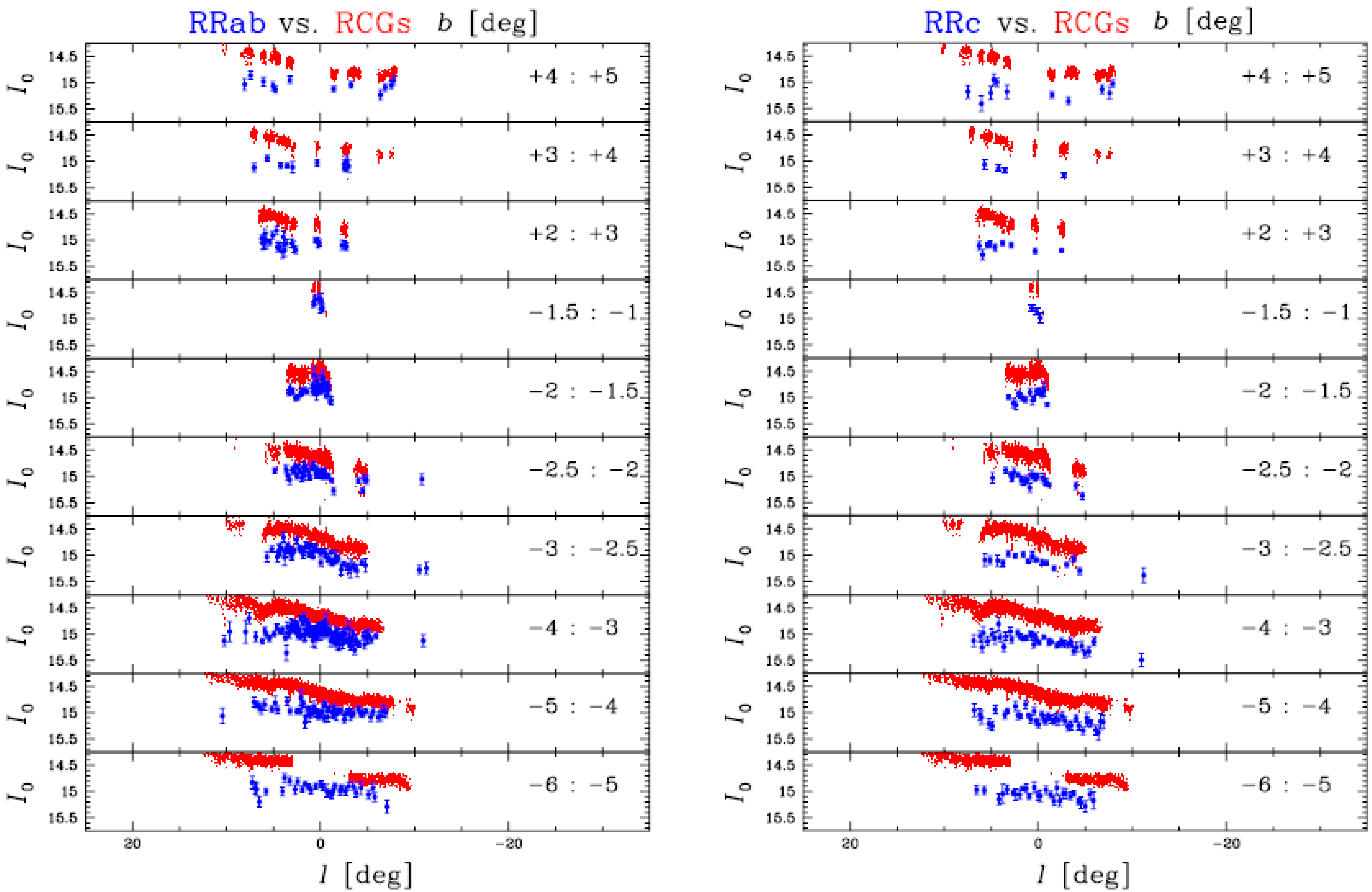

Apparent V magnitude of variable star RR Lyr
7
7.2
7.4
7.6
7.8
8
8.2
0
0.5
1
1.5
2
2.5
3
Time (days)

11,000 RR Lyrae Stars in Bulge



Pietrukowicz et al. 2012, ApJ, 750, 169

11,000 RR Lyrae Stars in Bulge



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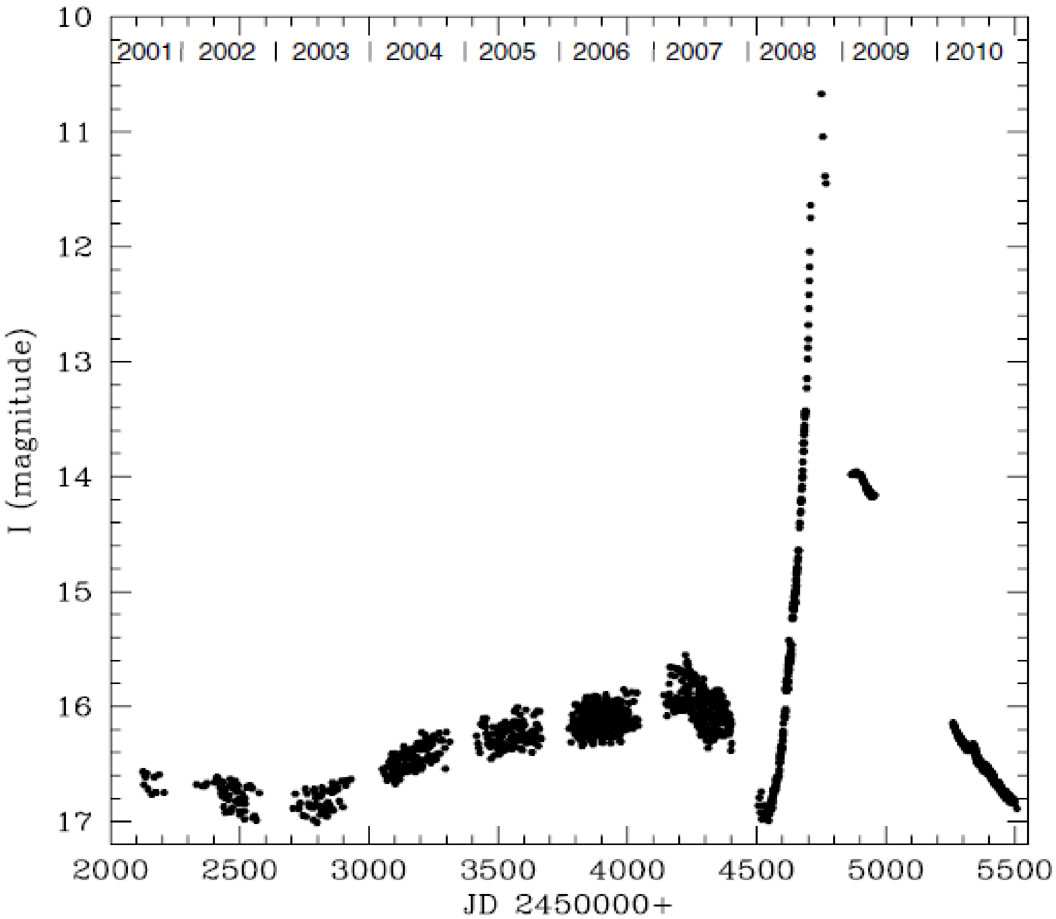
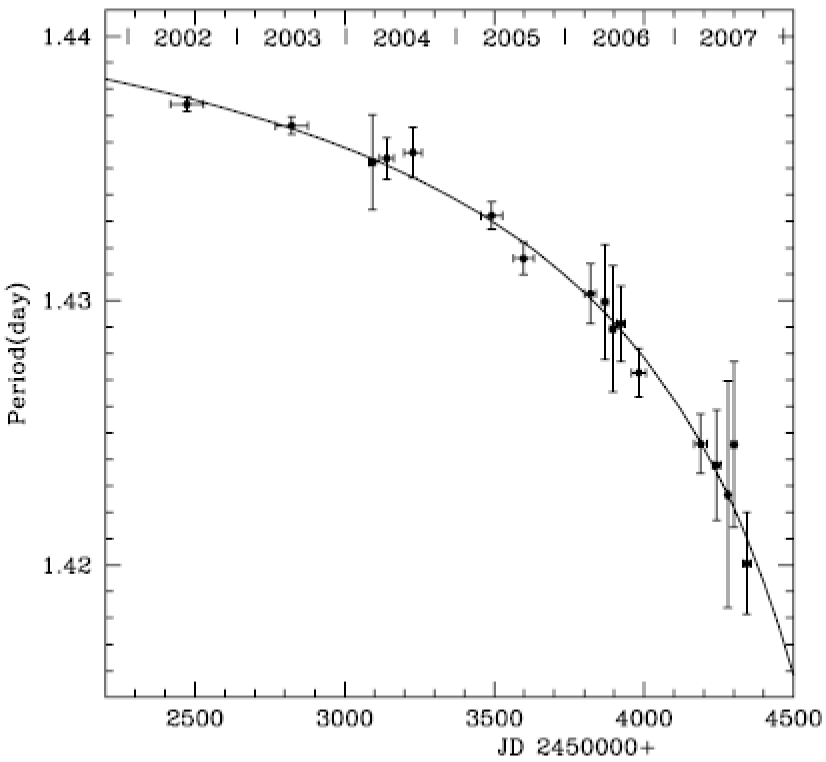
- Novae, ... and much more

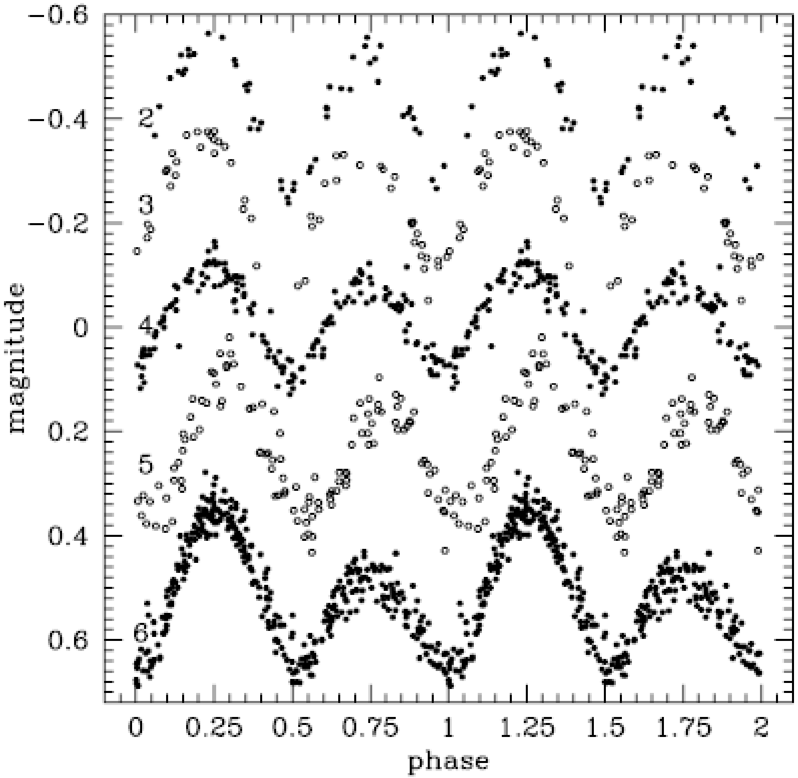
Variable Stars: Rare Merging Binaries



Tylenda et al. 2011, A&A, 528, 114

Variable Stars: Rare Merging Binaries

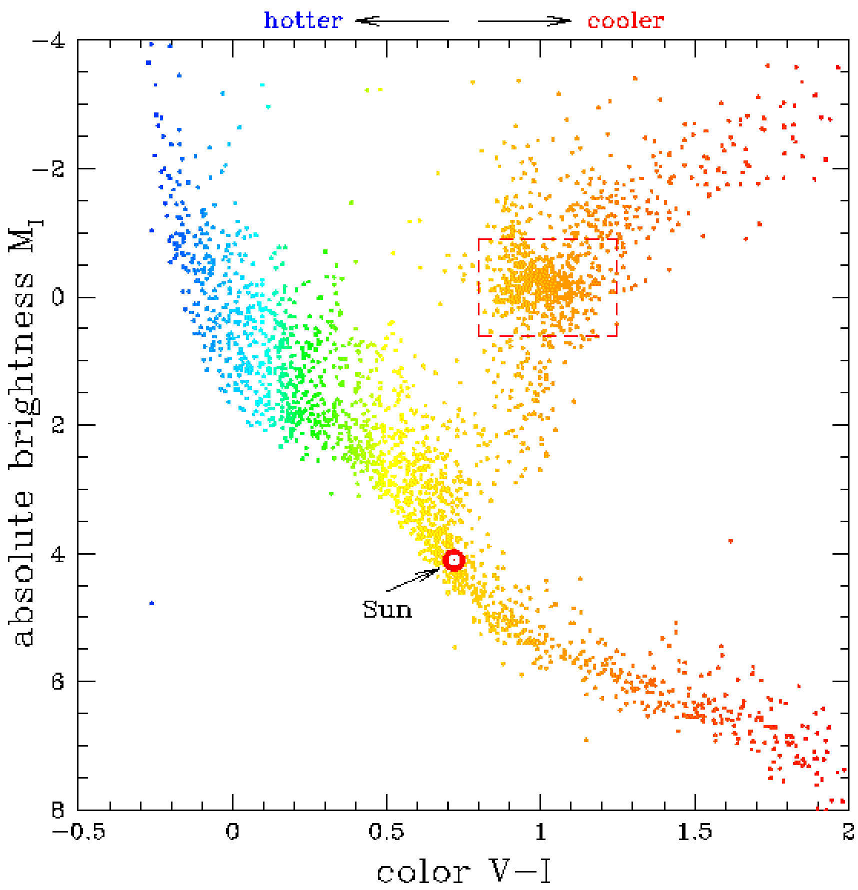




Tylenda et al. 2011, A&A, 528, 114

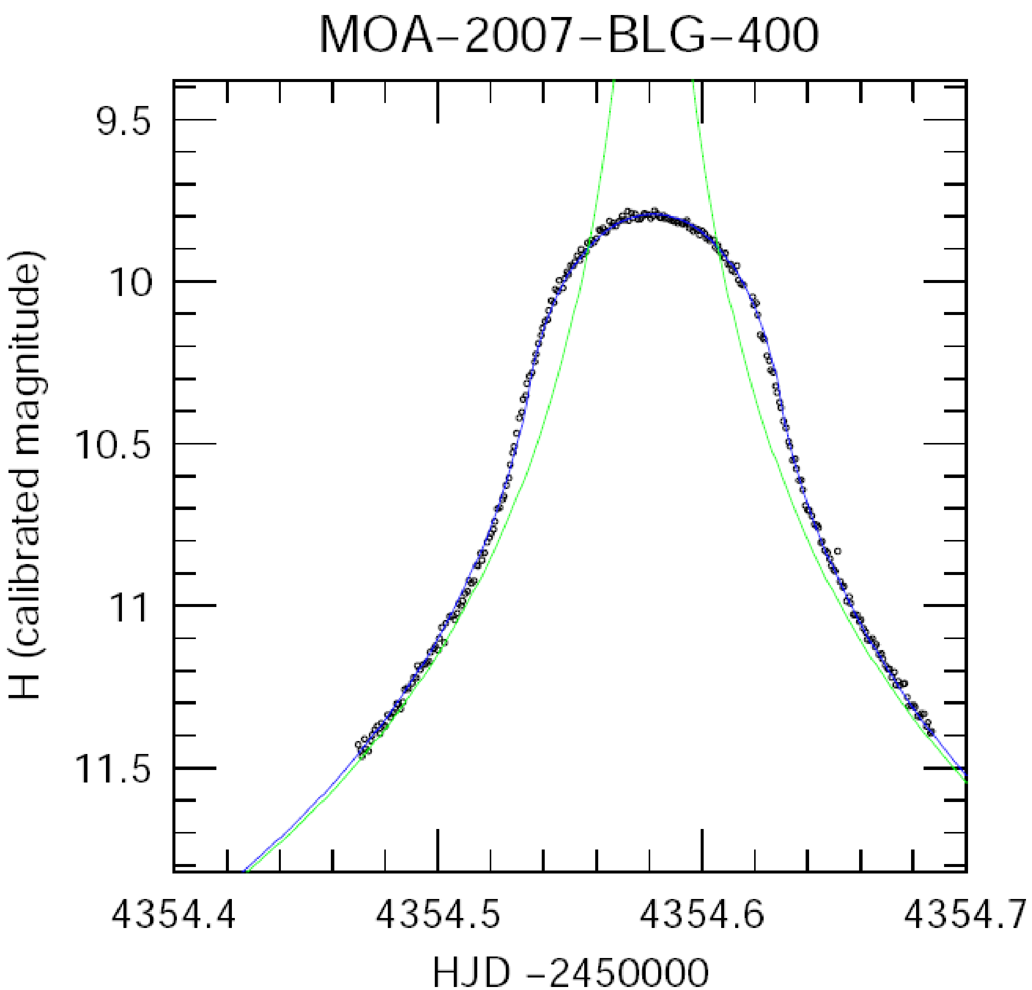
Galactic Structure and Dust

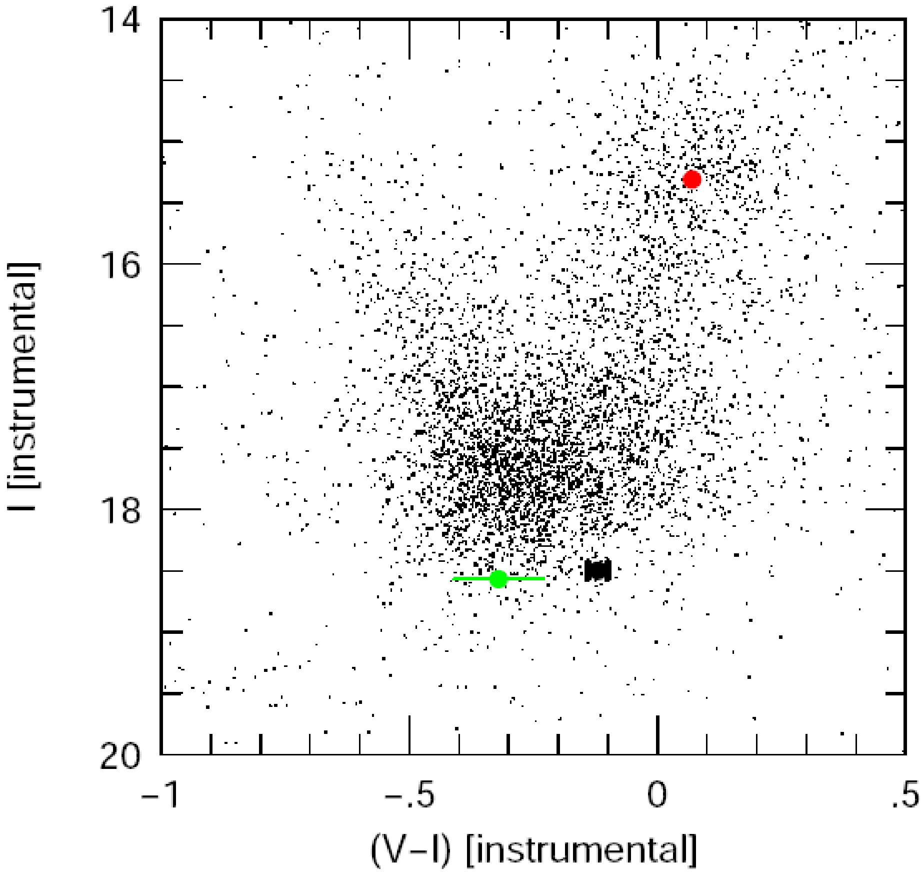
(mainly from Red Clump)



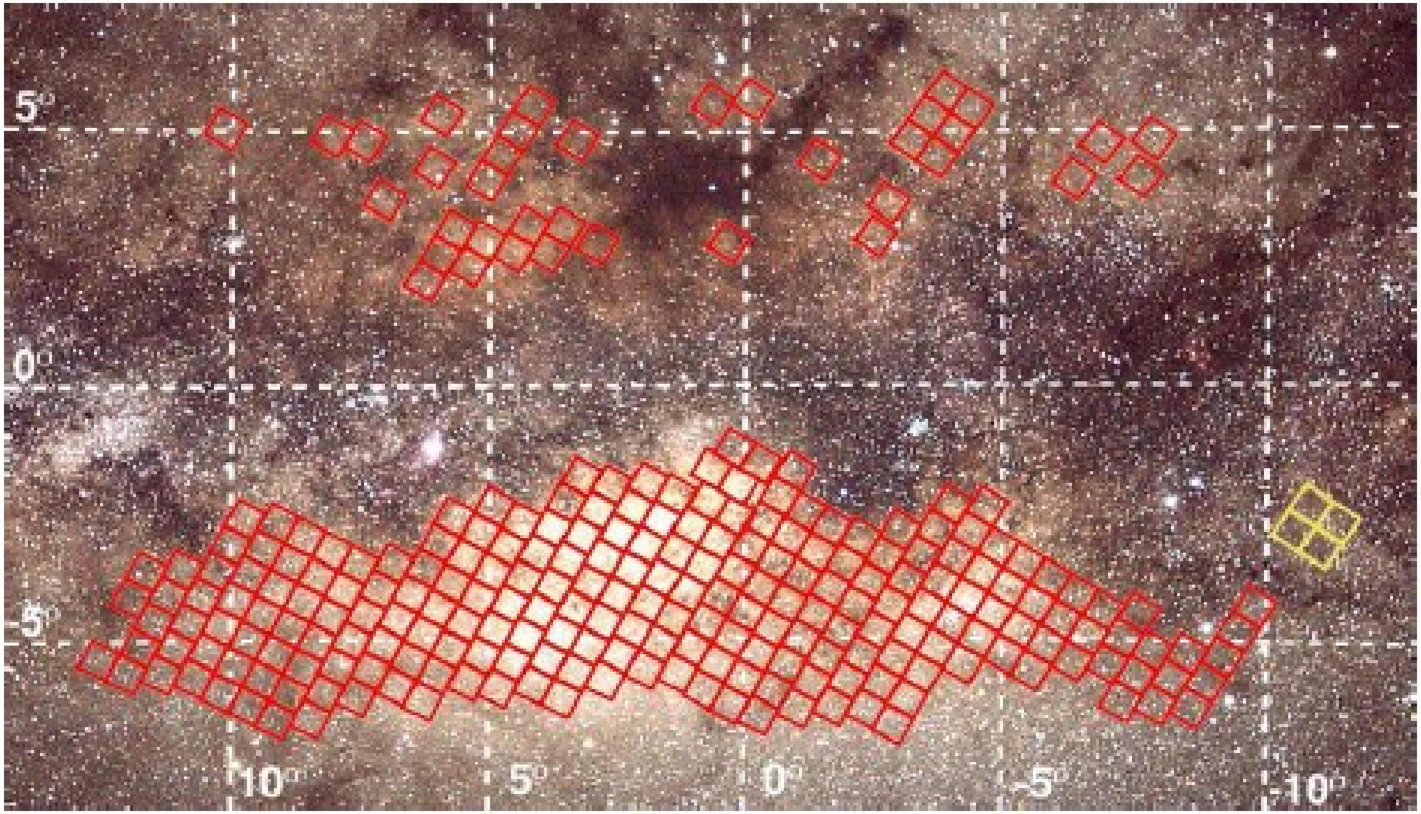
Needed to measure θ_E:

Standard Sky-Plane Rulers



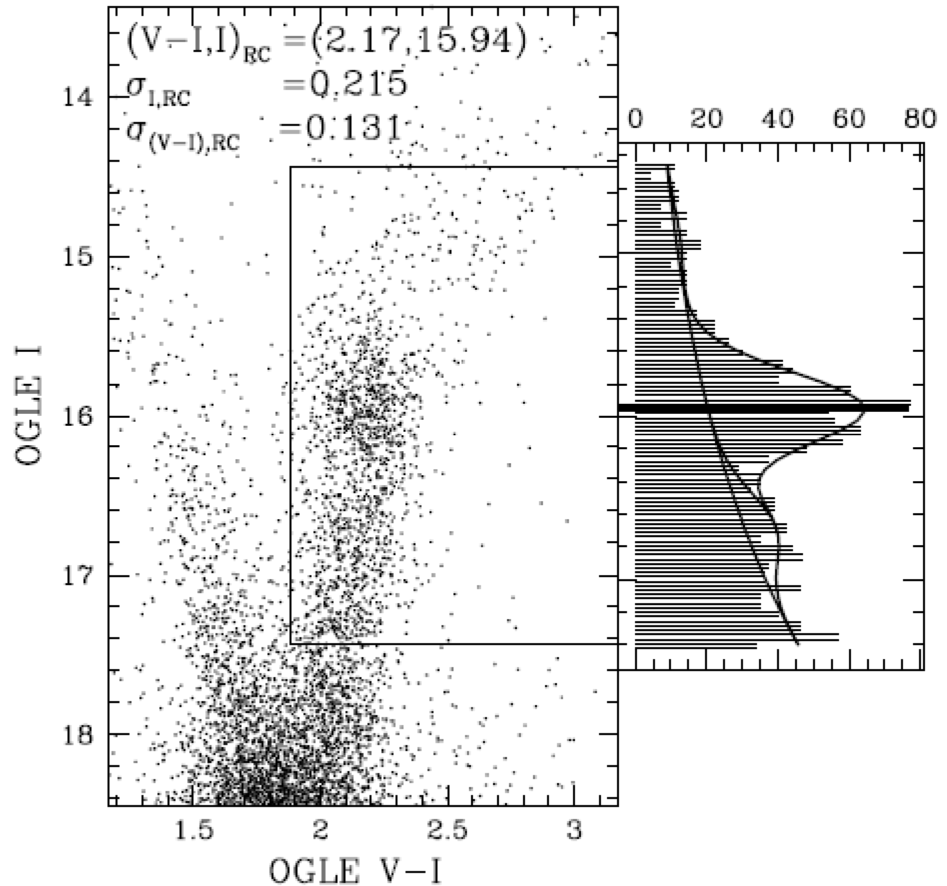


Clump: Standard Candle
Probe of Bulge



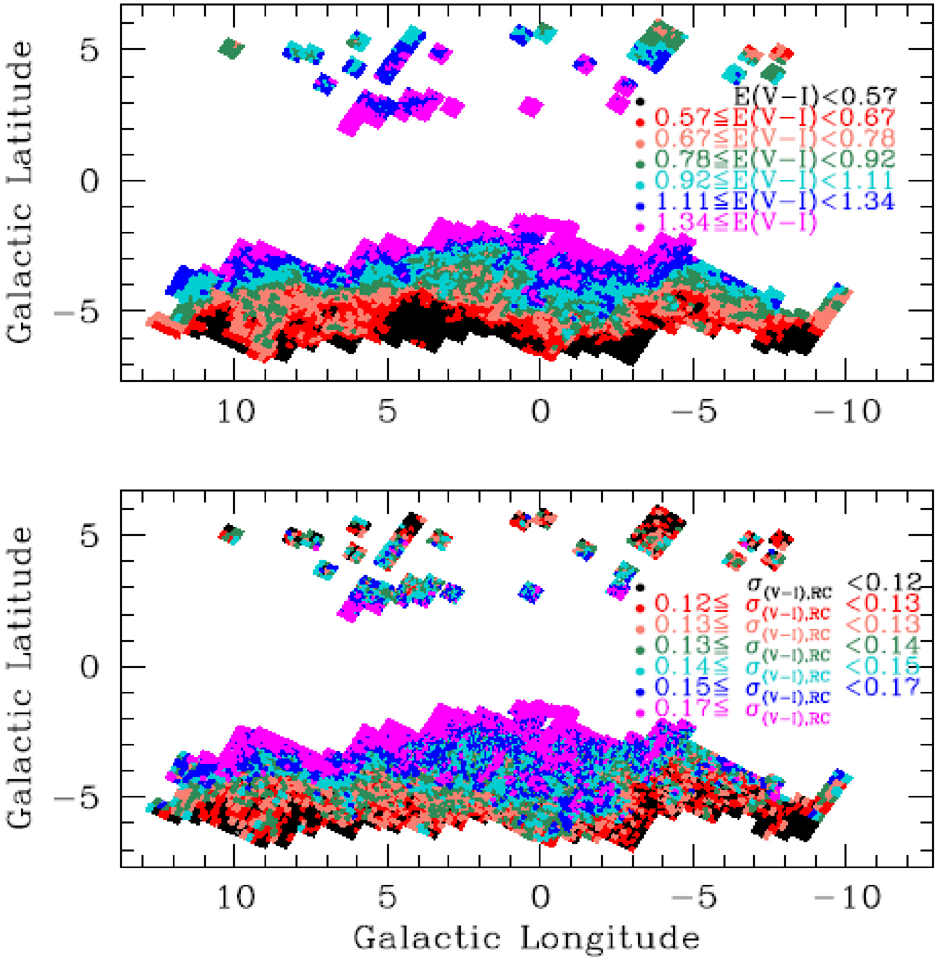
Nataf et al. 2013, ApJ, 769, 88

Clump: Standard Candle Probe of Bulge



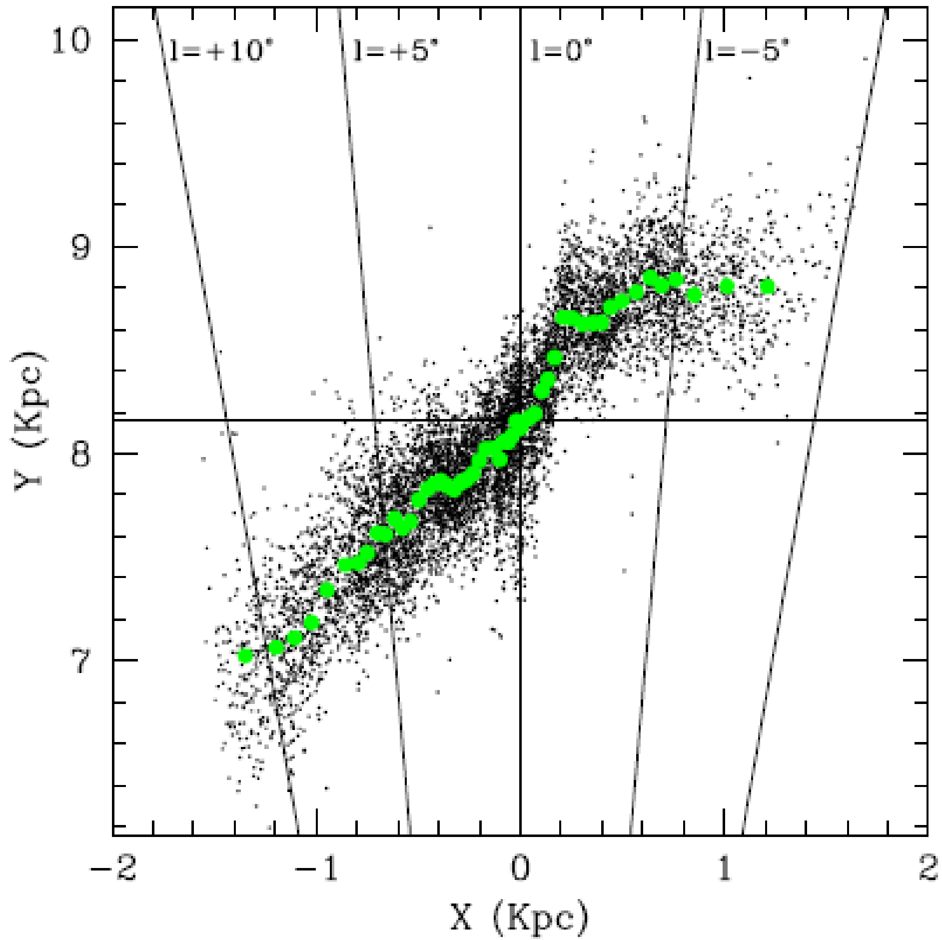
Nataf et al. 2013, ApJ, 769, 88

Clump: Extinction Probe



Nataf et al. 2013, ApJ, 769, 88

Clump: Distance Probe



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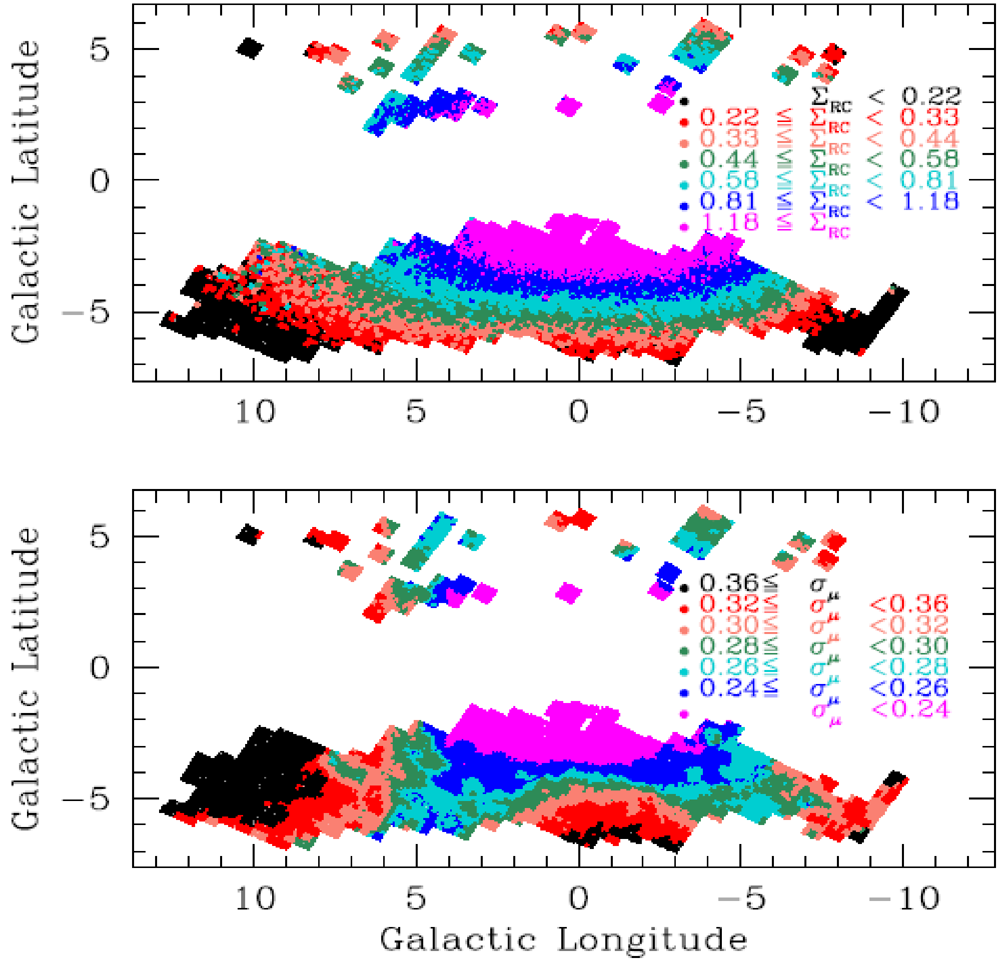
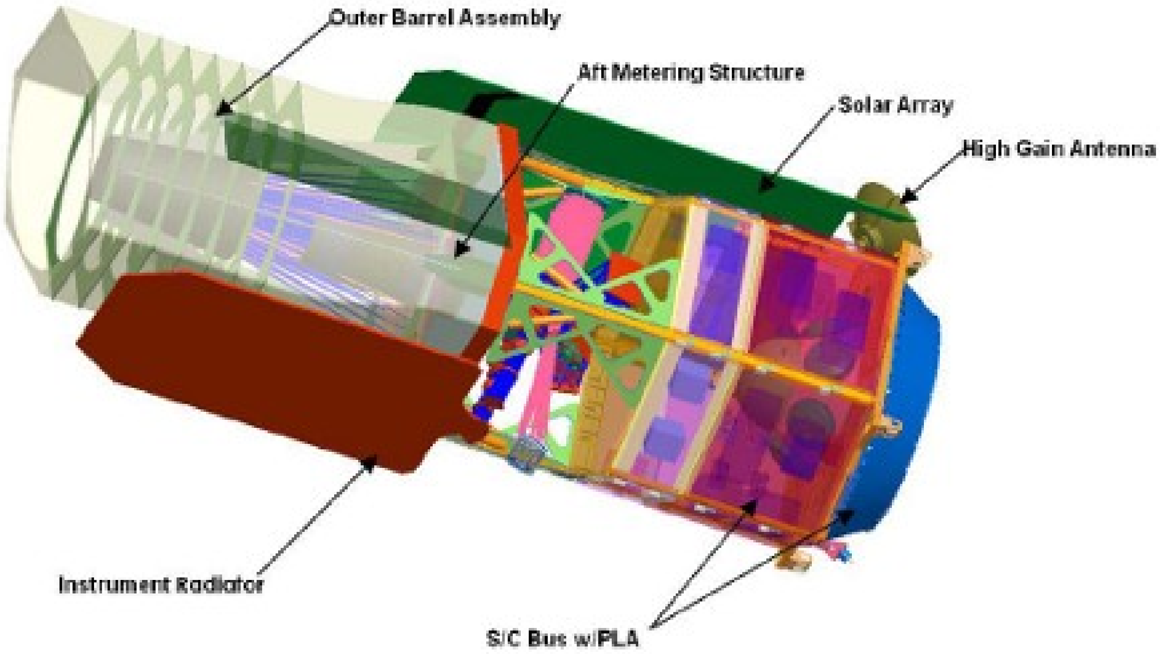
Clump: Density and Depth Probes



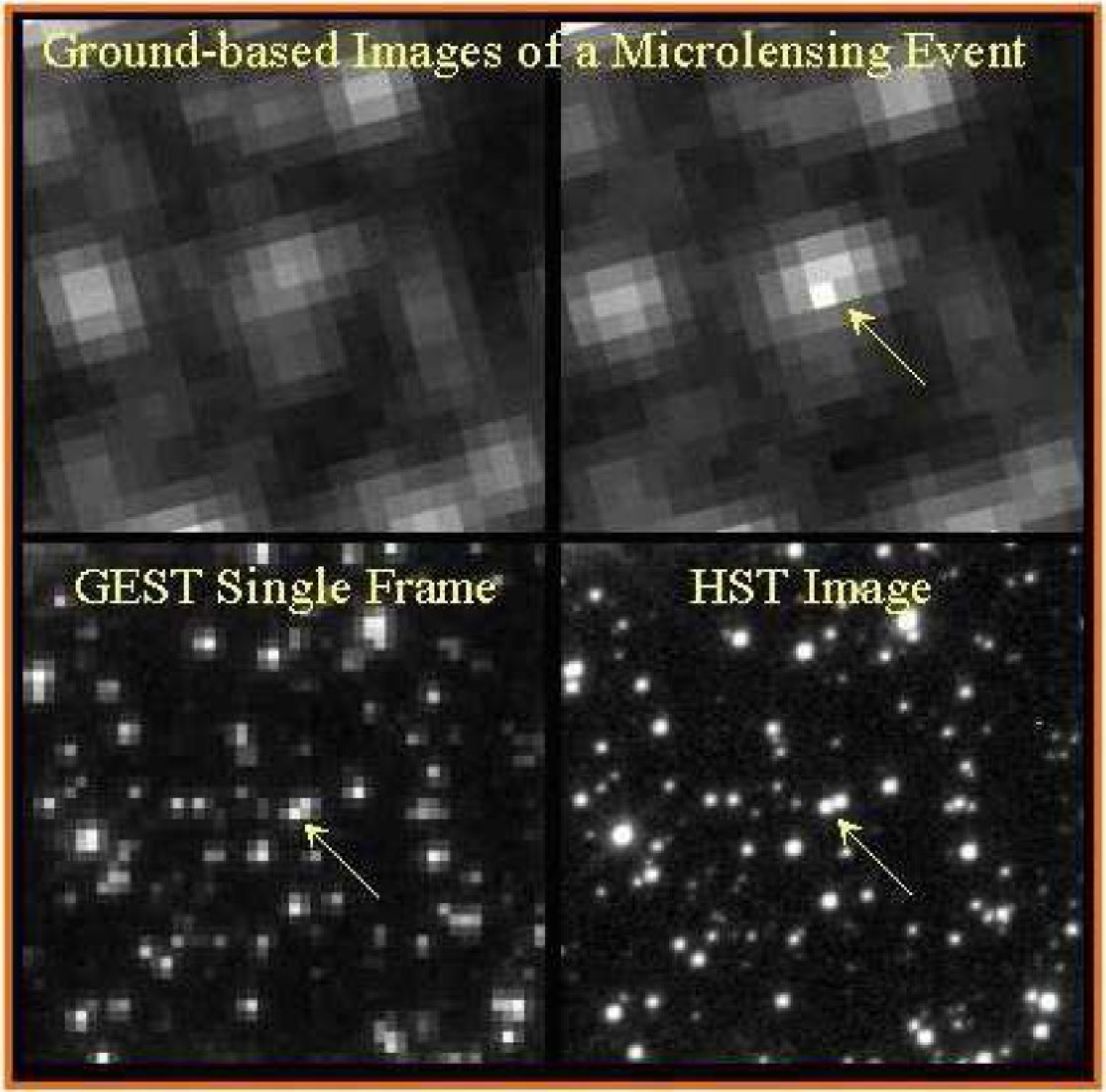
Nataf et al. 2013, ApJ, 769, 88

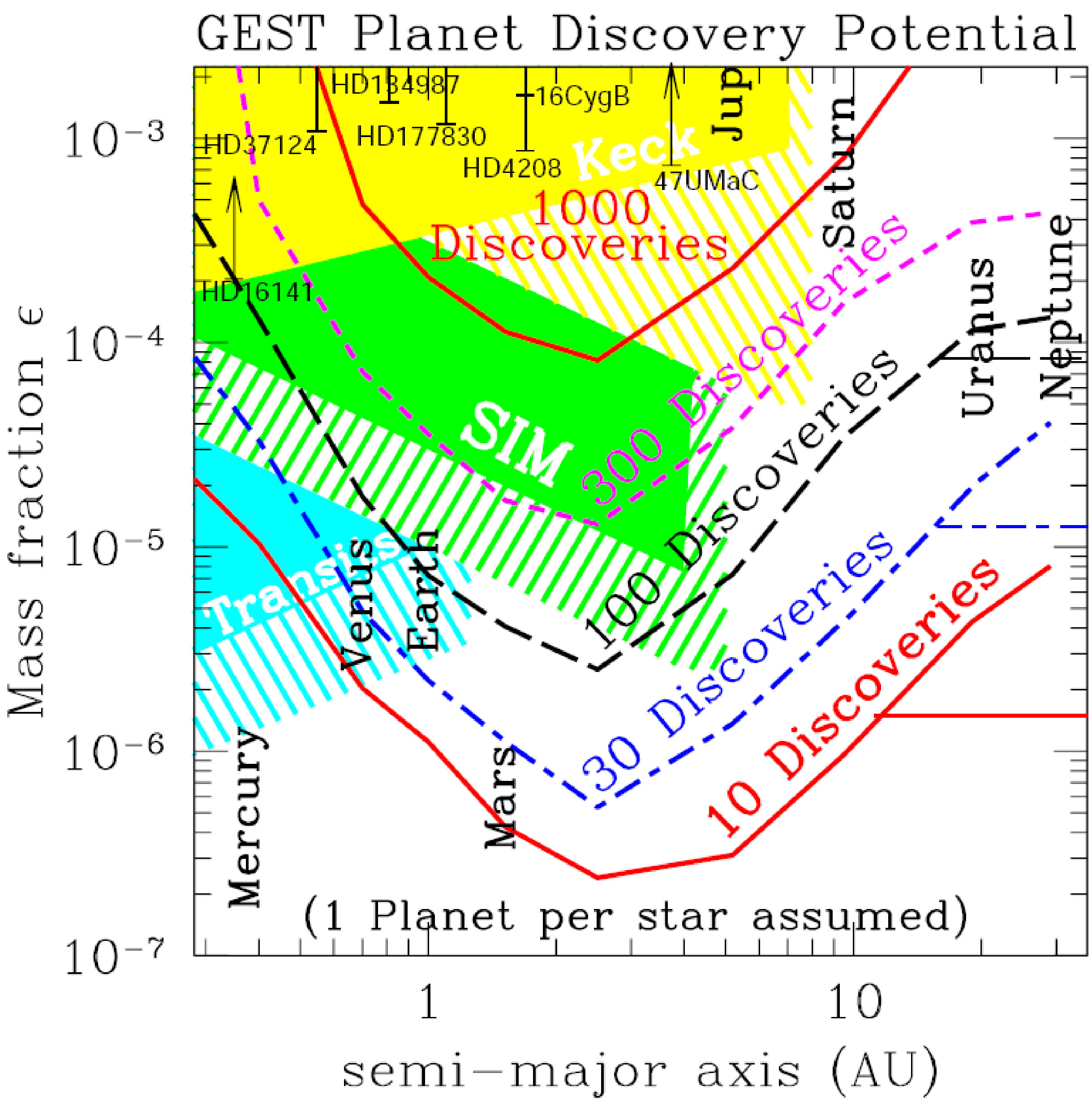
WFIRST



Outer Barrel Assembly
Aft Metering Structure
Solar Array
High Gain Antenna
Instrument Radiator
S/C Bus w/PLA

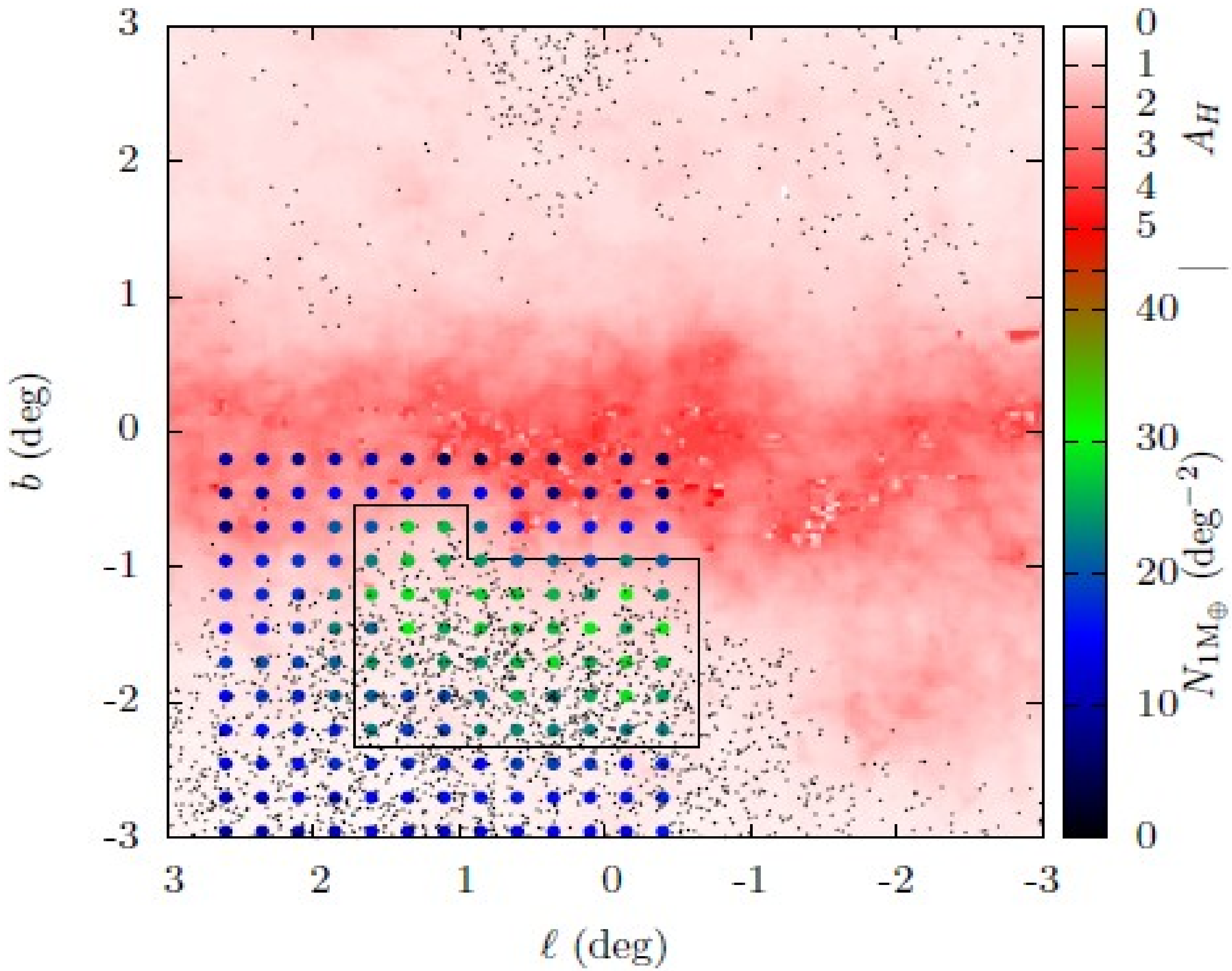
Seeing Better In Space (also weather)





Bennett & Rhie 2002, ApJ, 574, 985

WFIRST Microlensing Field

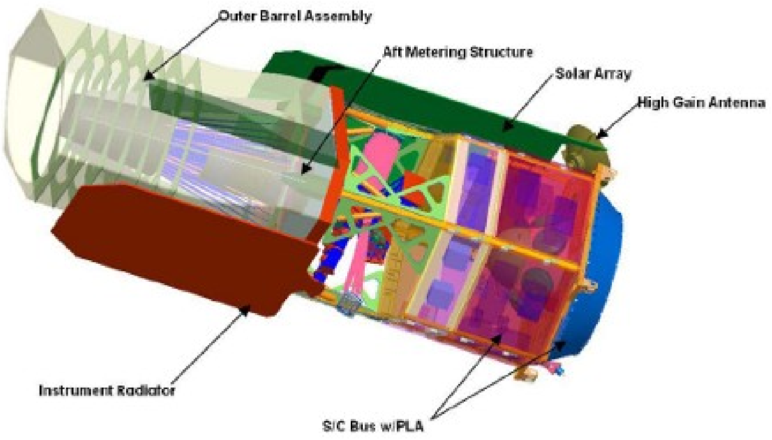


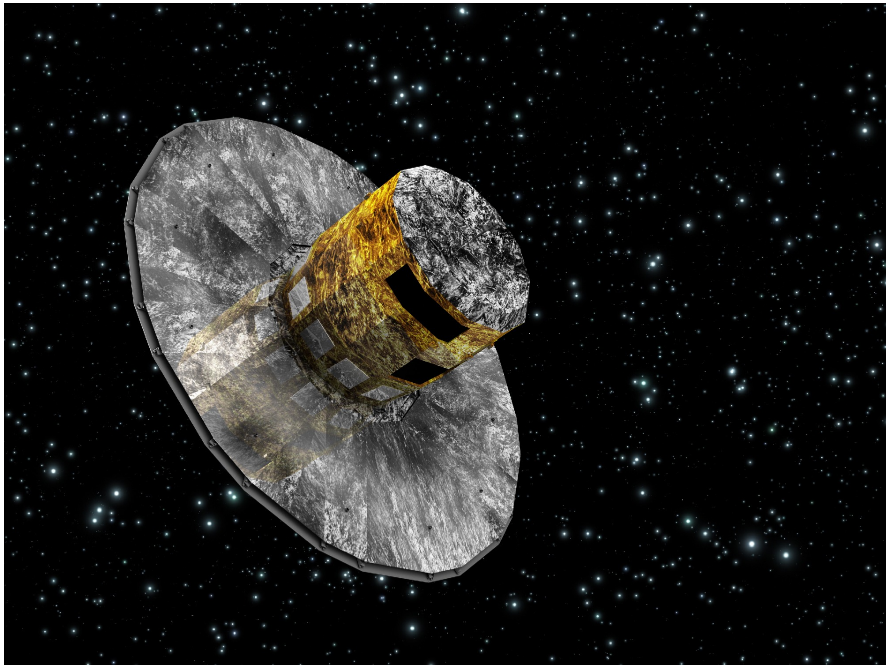
WFIRST "Microlensing" Survey Characteristics

- 40,000 images (52 sec)
- 2.8 sq.deg.
- 6 continuous 72-day campaigns (at quadrature)
- 100 images per day
- SNR = 10^{0.4(Hzero-H)} Hzero = 26.1

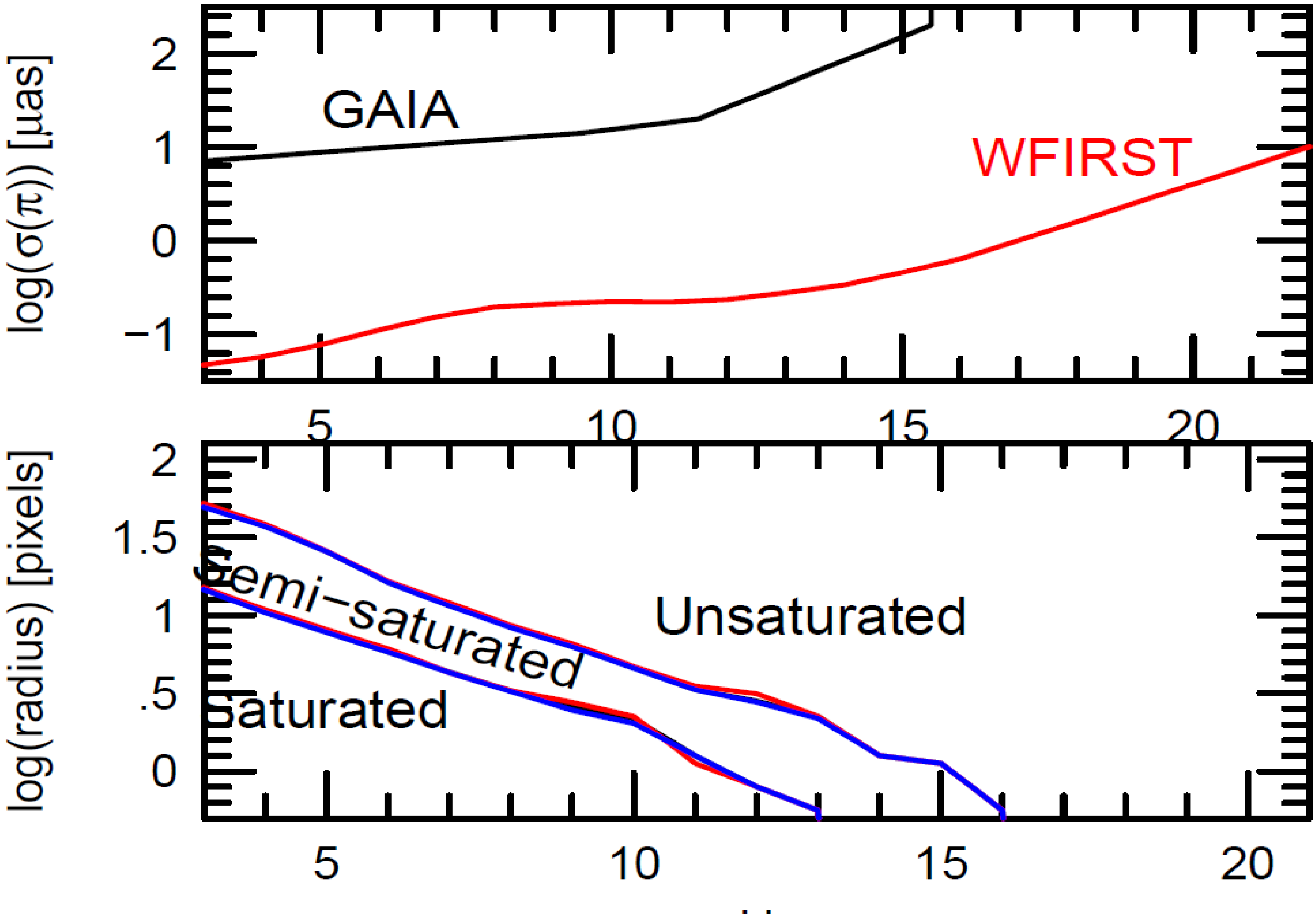
Gould 2014 JKAS, 47, 279

WFIRST vs. GAIA





WFIRST vs GAIA
Parallax Precision

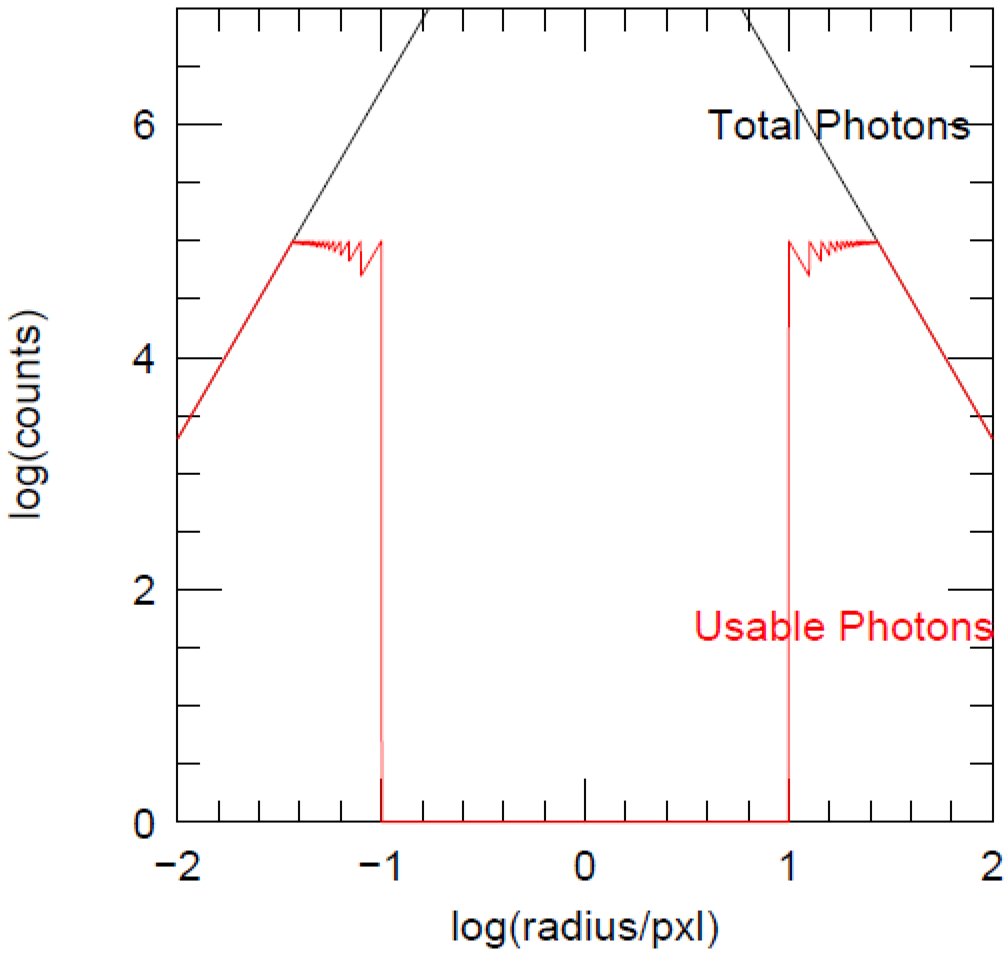


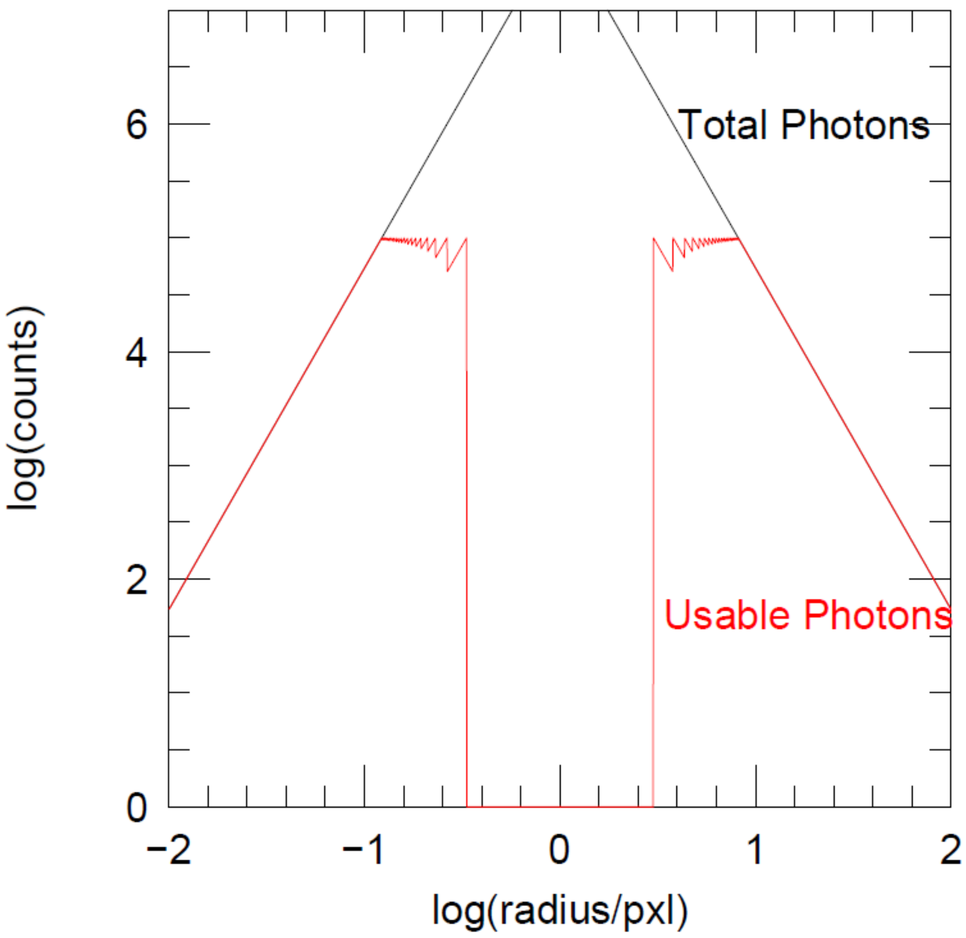
Non-Microlensing WFIRST Science: Ultra-precise Parallaxes

- H<14.0; $\sigma(\pi) < 0.3$ μas; 1,000,000 stars
- H<19.6; $\sigma(\pi) < 3.7$ μas; 40,000,000 stars
- H<21.6; $\sigma(\pi) < 10$ μas; 120,000,000 stars

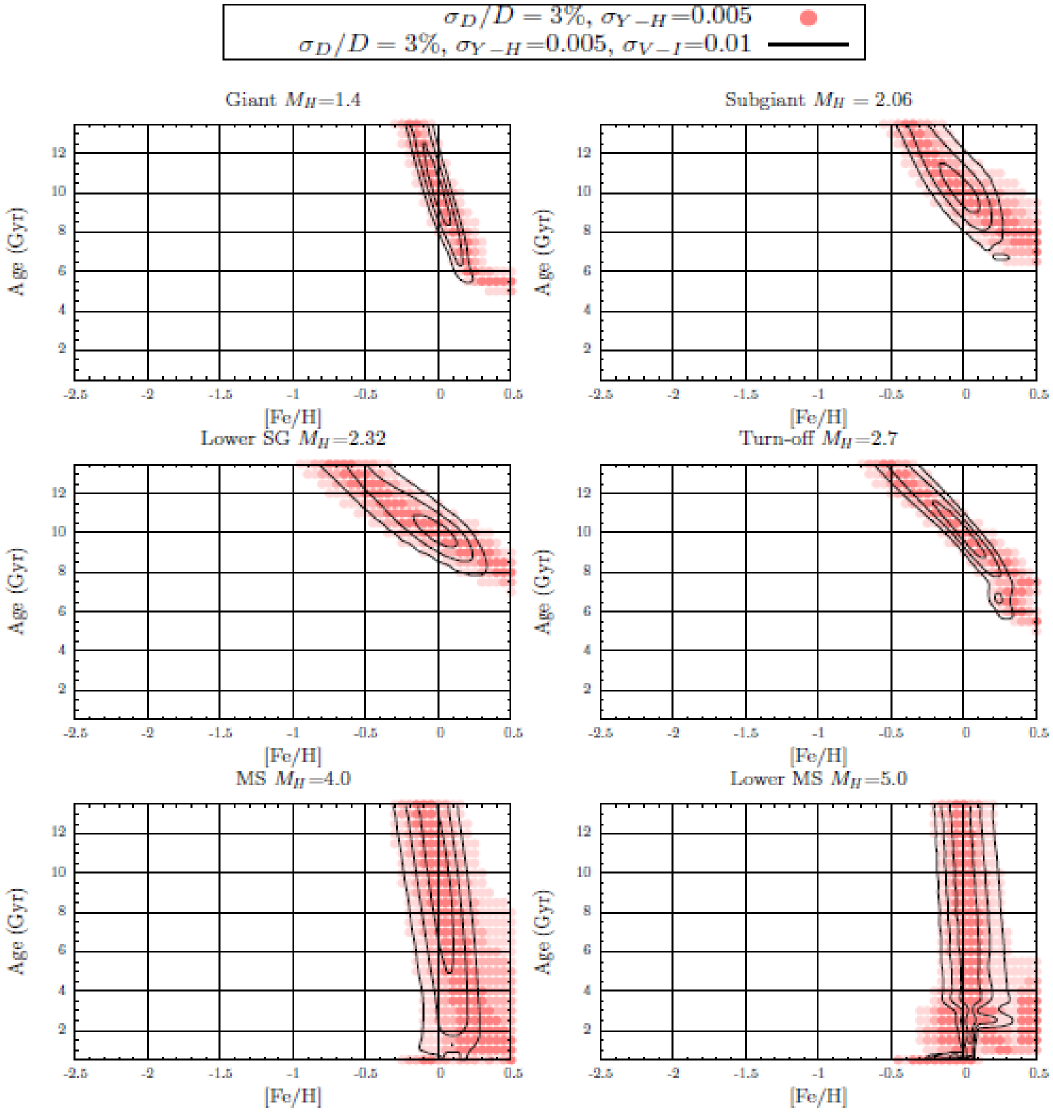
Gould, Huber, Penny, Stello, 2015 JKAS, in press

WFIRST
Astrometric Information Flow

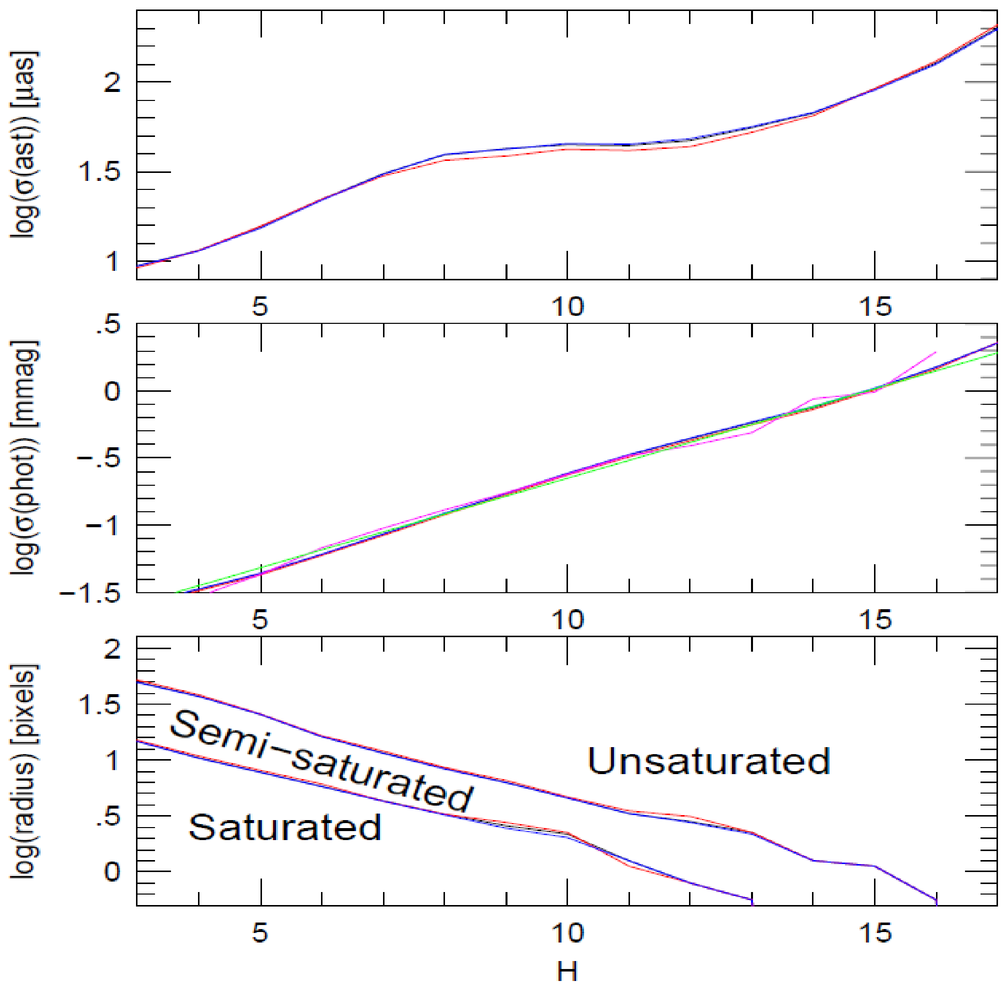




Age & [Fe/H] for 7,000,000 stars (first four panels) [needs V/I-band]

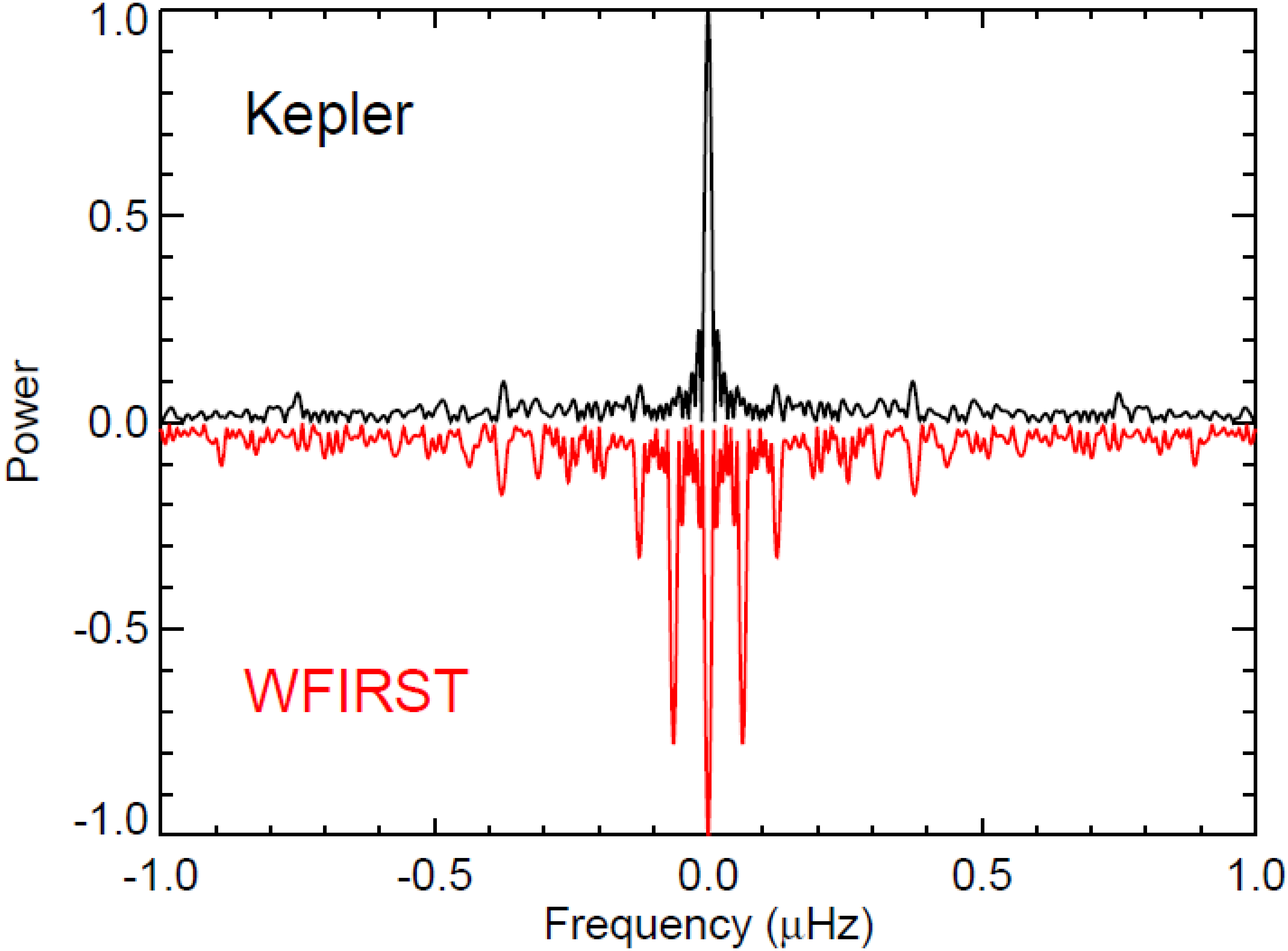


Non-Microlensing WFIRST Science:
Ultra-precise Parallaxes and Photometry



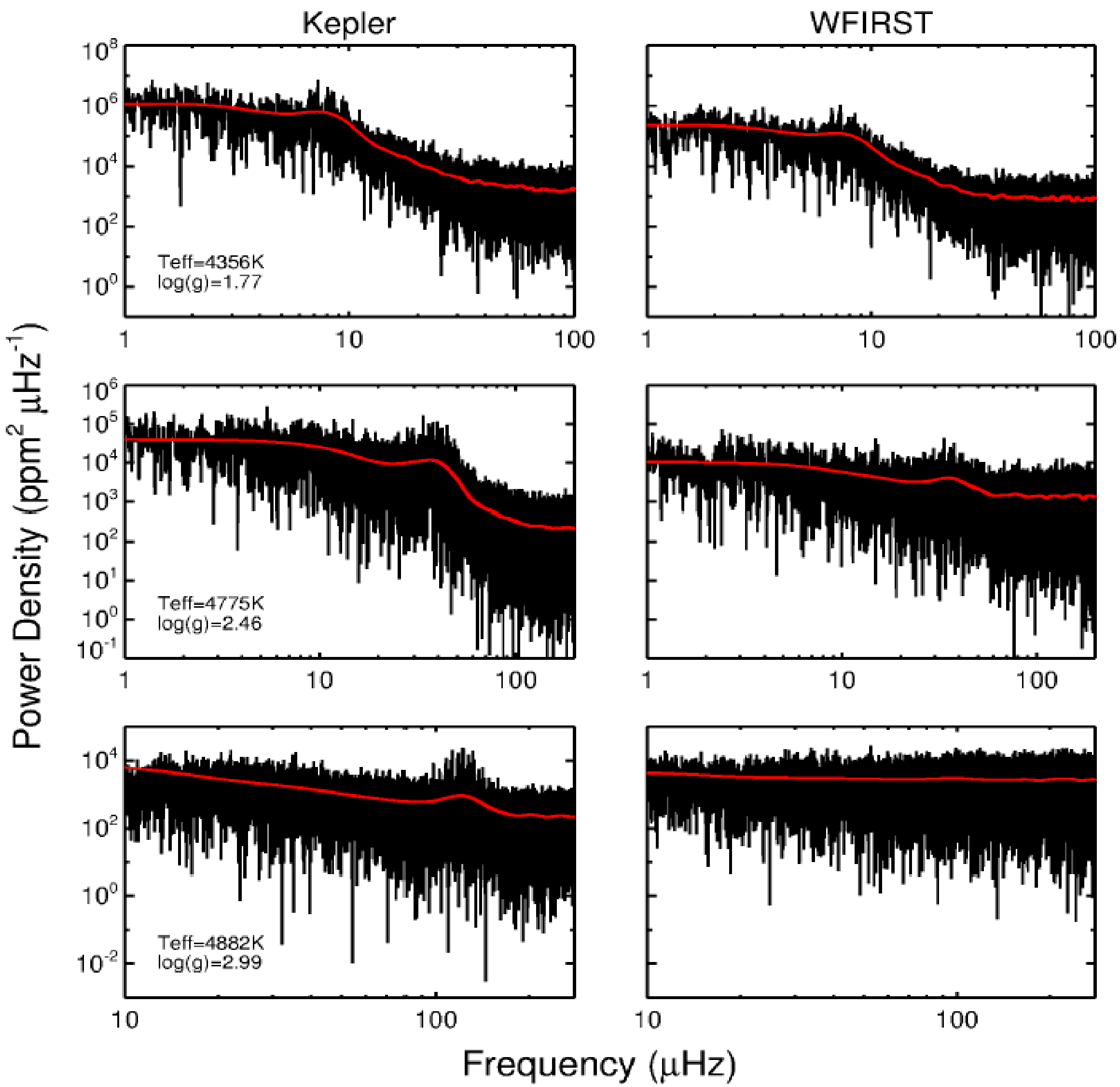
Gould, Huber, Penny, Stello, 2015 JKAS, 48, 93

Non-Microlensing WFIRST Science:
Asteroseismic Window Function



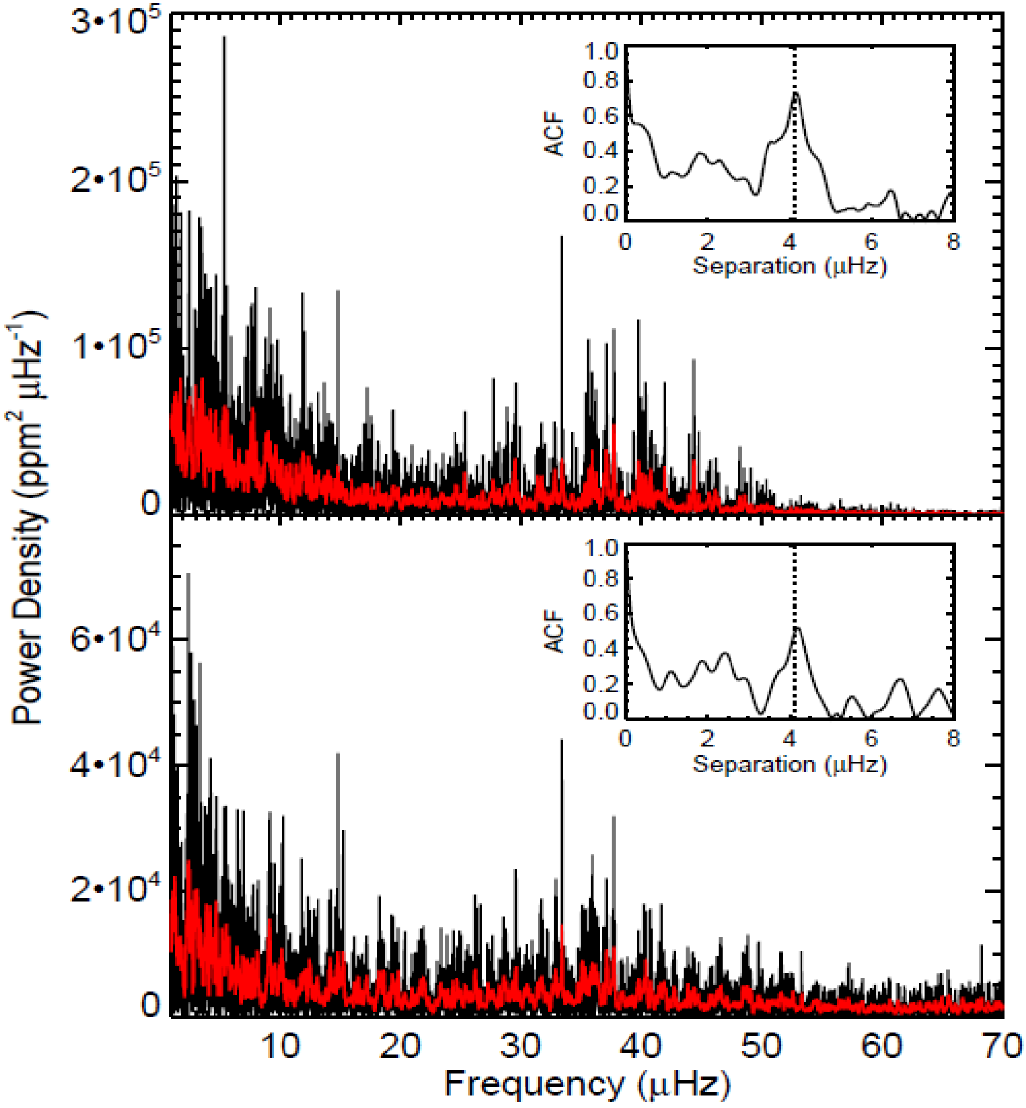
Gould, Huber, Penny, Stello, 2015, JKAS, 48, 93

Non-μlens WFIRST Science: ν_{max}



Gould, Huber, Penny, Stello, 205, JKAS, 48, 93

Non-μlens WFIRST Science: Δν



Gould, Huber, Penny, Stello, 2015, JKAS, 48, 93

$\Delta\nu$ & ν_{max}

$$\frac{\rho}{\rho_\odot} \simeq \left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^2;$$

$$\frac{g}{g_\odot} \simeq \frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

Δν & ν_{max}

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$$\frac{R}{R_\odot} \simeq \frac{\nu_{\rm max}}{\nu_{\rm max,\odot}} \left(\frac{\langle \Delta\nu_{nl} \rangle}{\langle \Delta\nu_{nl} \rangle_\odot} \right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}} \right)^{1/2}$$

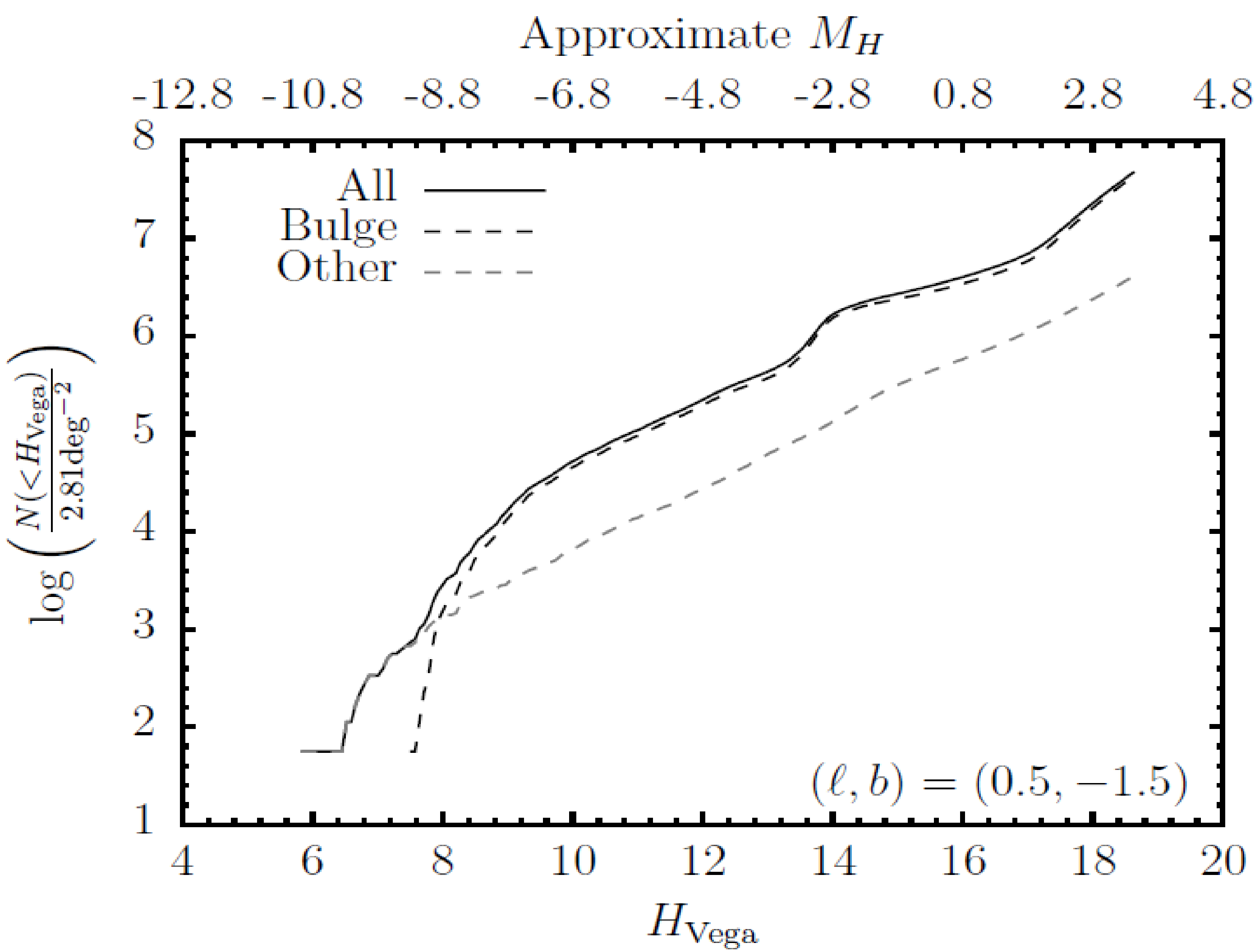
$\Delta\nu$ & ν_{max}

$$\frac{\rho}{\rho_\odot} \simeq \left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^2; \qquad \frac{g}{g_\odot} \simeq \frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

$$\frac{R}{R_\odot} \simeq \frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{-2}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

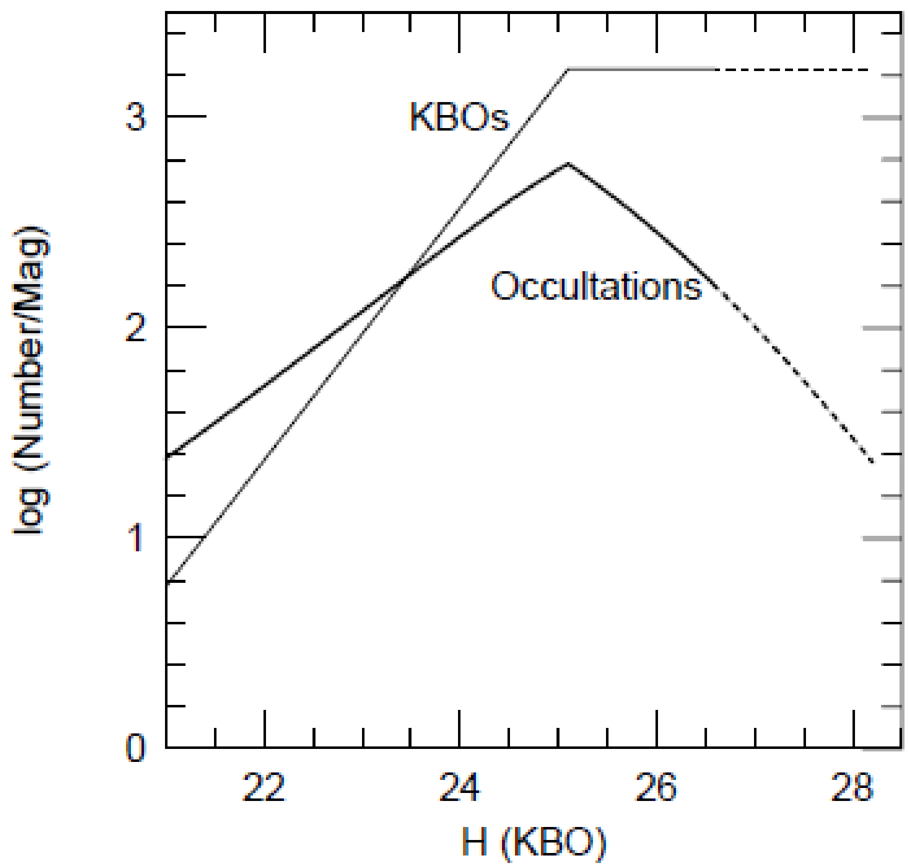
$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)^3\left(\frac{\langle\Delta\nu_{nl}\rangle}{\langle\Delta\nu_{nl}\rangle_\odot}\right)^{-4}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}$$

Non-μlens WFIRST Science:
10% Disk Stars



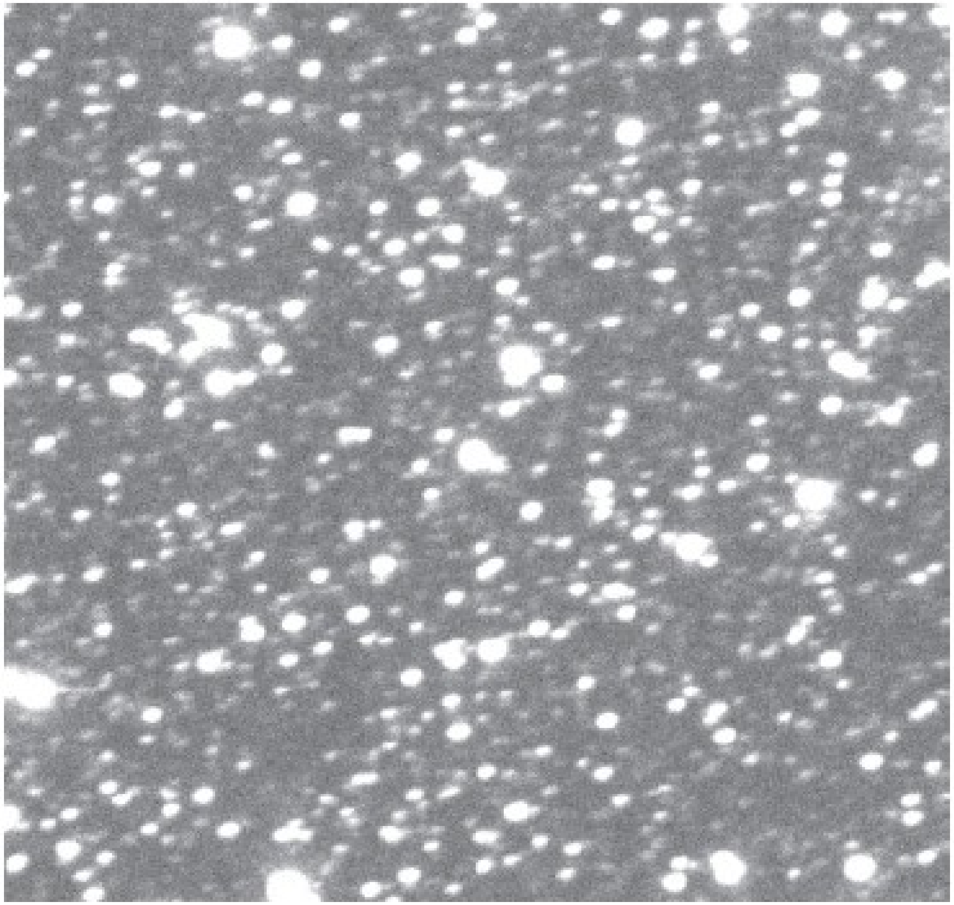
Gould, Huber, Penny, Stello, 2015, JKAS, 48, 93

Non-μlens WFIRST Science: KBOs



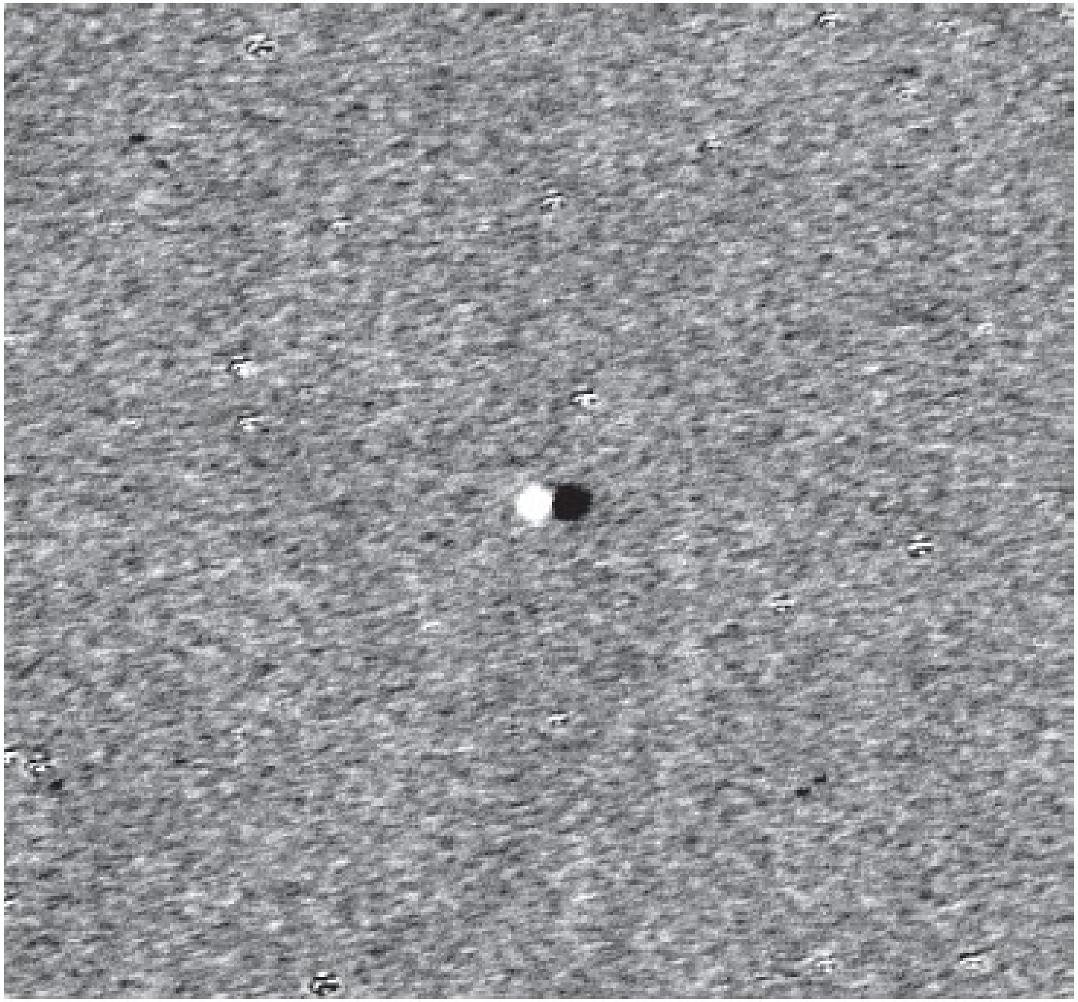
Gould 2014 JKAS, 47, 279

KBOs possible in microlensing fields?



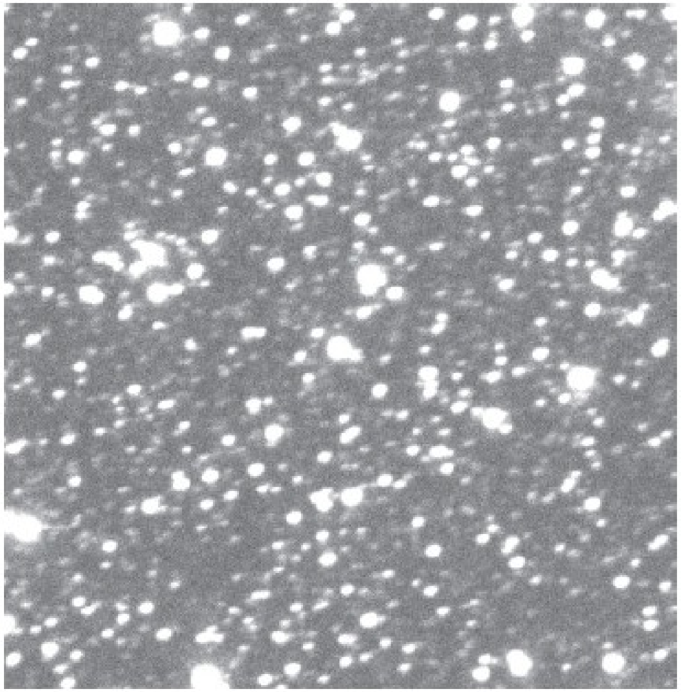
Shepard et al. 2011, AJ, 142, 98

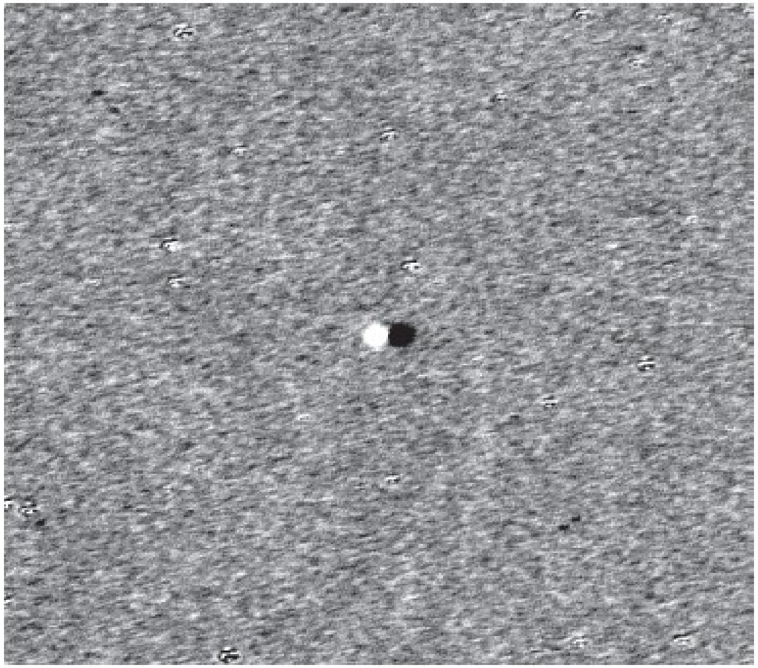
Yes! Microlensing fields are not crowded ...



Sheppard et al. 2011, AJ, 142, 98

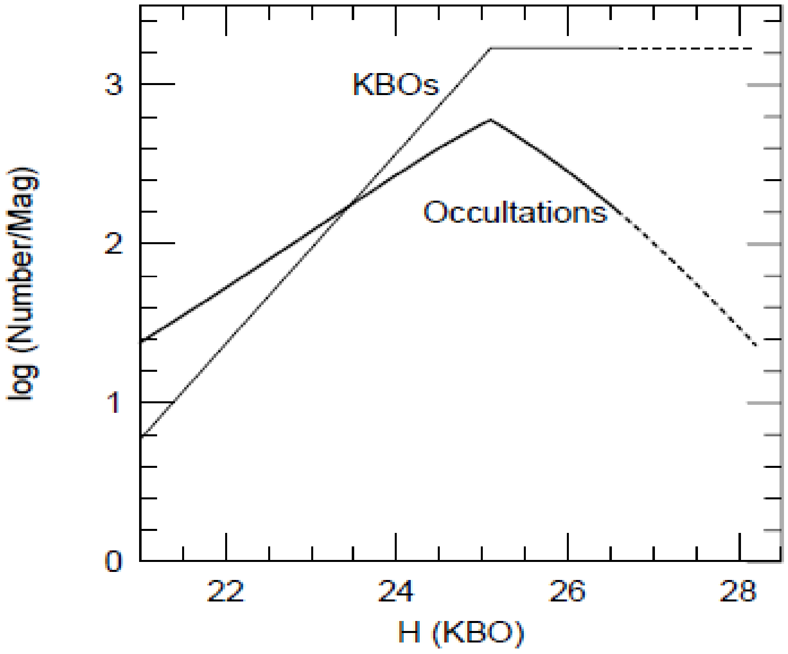
Yes! Microlensing fields are not crowded after image subtraction!





Sheppard et al. 2011, AJ, 142, 98

Non-μlens WFIRST Science: KBO Precision orbits

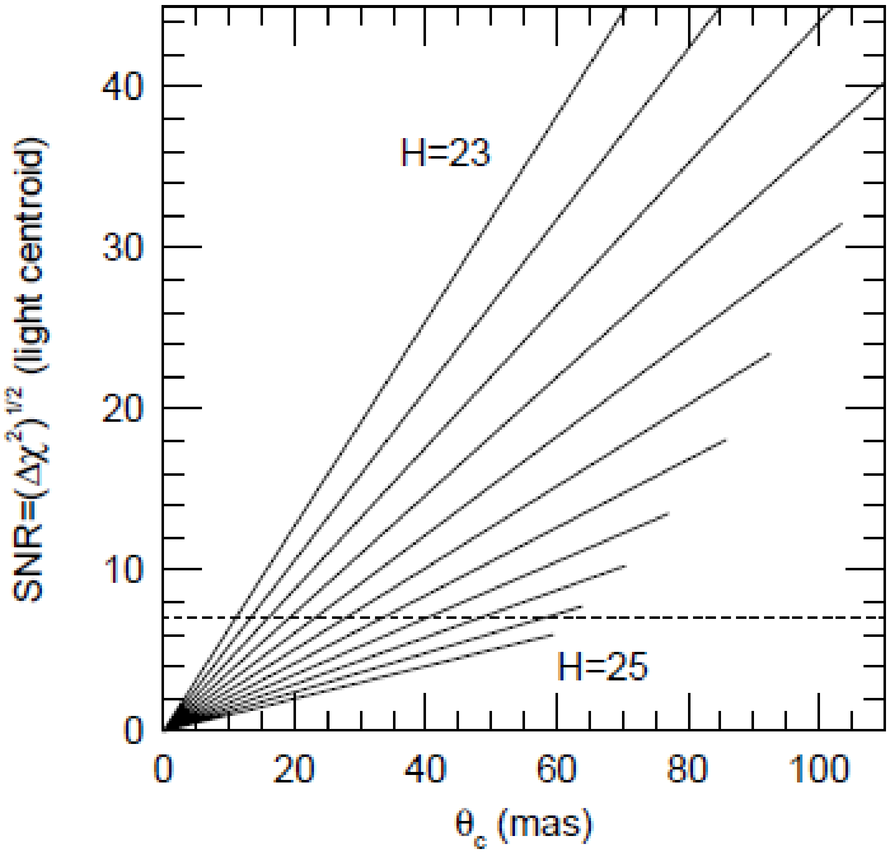


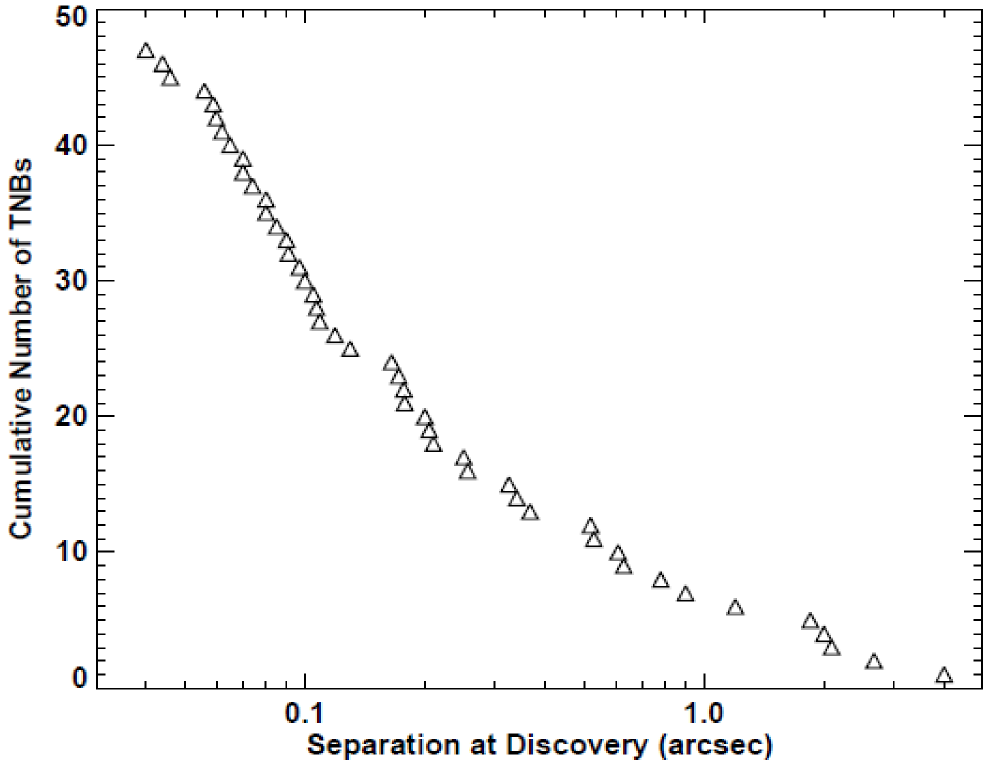
$$\sigma(P)/P \sim 0.09\%$$

$$H \sim 25.1$$

Gould 2014 JKAS, 47, 279

Non-μlens WFIRST Science:
KBO Binaries





Gould 2014 JKAS, 47, 279

Noll et al. 2008

Non-μlens WFIRST Science: Transits:
-> Galactic Distribution of Hot Planets

- Bulge G dwarf: 8 mmag
- $\Delta\chi^2 = 100$ requires: $p_{transit} = 0.0025/(\delta/0.008)$
- Jupiters: $a < 160\ R_{sun}$; $P < 250$ days
- Neptunes: $a < 25\ R_{sun}$; $P < 15$ days
- Earths: (not feasible at bulge)

Non-μlens WFIRST Science: BH + NS in Wide Orbits

- BH+star (5+1) -> 500 μas orbit at P = 5 yr
  - ==> 50 σ detection for 120,000,000 stars
  - ==> 17 σ at P=1 yr
- NS+star (1.4+1) -> 270 μas orbit at P = 5 yr
  - ==> 27 σ detection for 120,000,000 stars
  - ==> 9 σ at P=1 yr

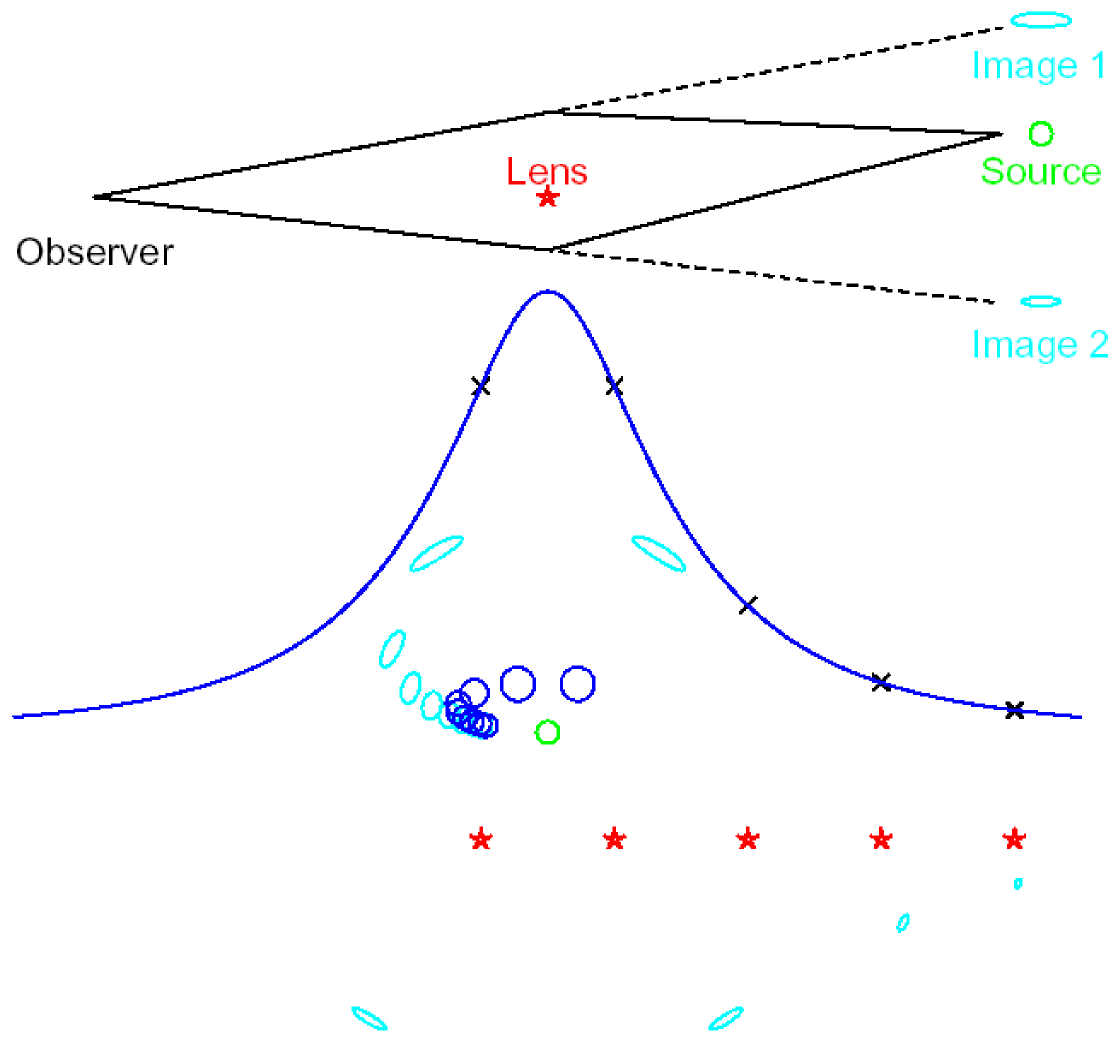
Non-Planet WFIRST μlens Science:

Isolated BH Mass & Velocity Functions

(Gould & Yee 2014 ApJ 784 64)

[Astrometric Microlensing]

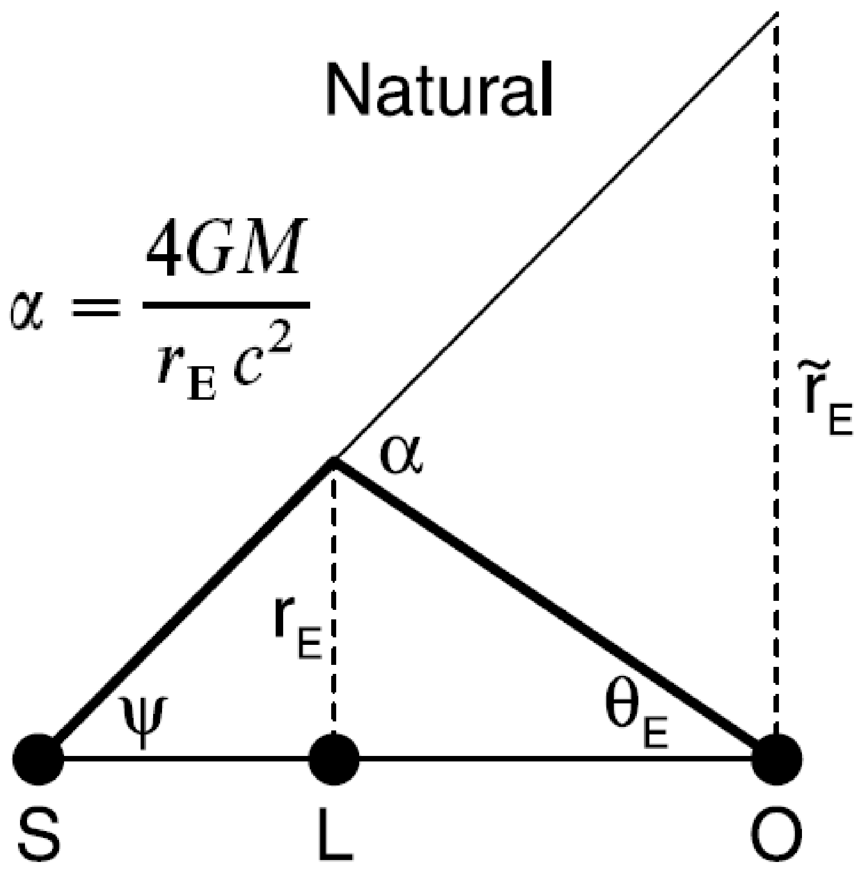
How Astrometric Microlensing Works



Non-Planet WFIRST μlens Science: Isolated BH Mass & Velocity Functions (Gould & Yee 2014 ApJ 784 64) [Astrometric Microlensing]

- $\Delta\boldsymbol{\theta} = [\mathbf{u}/(u^2 + 2)]\theta_E$
- $\theta_E \sim 500\ \mu as$
- $\Delta\theta \sim 150\ \mu as$

Relation of Mass and Distance to Lensing Observables



$$\alpha/\tilde{r}_E = \theta_E/r_E$$

$$\theta_E \tilde{r}_E = \alpha r_E = \frac{4GM}{c^2}$$

$$\theta_E = \alpha - \psi = \frac{\tilde{r}_E}{D_l} - \frac{\tilde{r}_E}{D_s} = \frac{\tilde{r}_E}{D_{rel}}$$

$$\tilde{r}_E = \sqrt{\frac{4GMD_{rel}}{c^2}} \qquad \theta_E = \sqrt{\frac{4GM}{D_{rel} c^2}}$$

Non-Planet WFIRST μlens Science: Isolated BH Mass & Velocity Functions (Gould & Yee 2014 ApJ 784 64) [Astrometric Microlensing]

- $\Delta\boldsymbol{\theta} = [\mathbf{u}/(u^2 + 2)]\theta_E$
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- $\Delta\theta \sim 150\ \mu as$