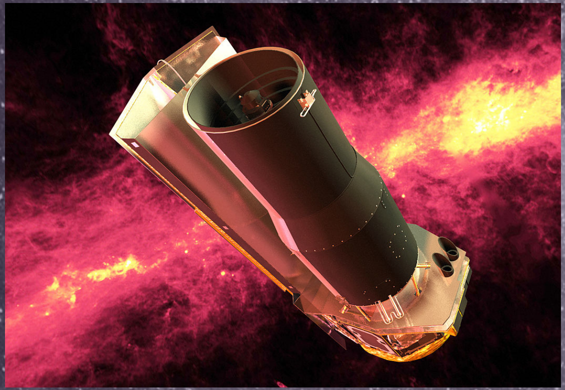
IPAC *WFIRST* Microlensing Primer Series IV:

Results from and Future Directions for Space-based Microlensing Surveys



Yossi Shvartzvald

Calen B. Henderson

NPP Fellows @ JPL

IPAC *WFIRST* Microlensing Primer Series

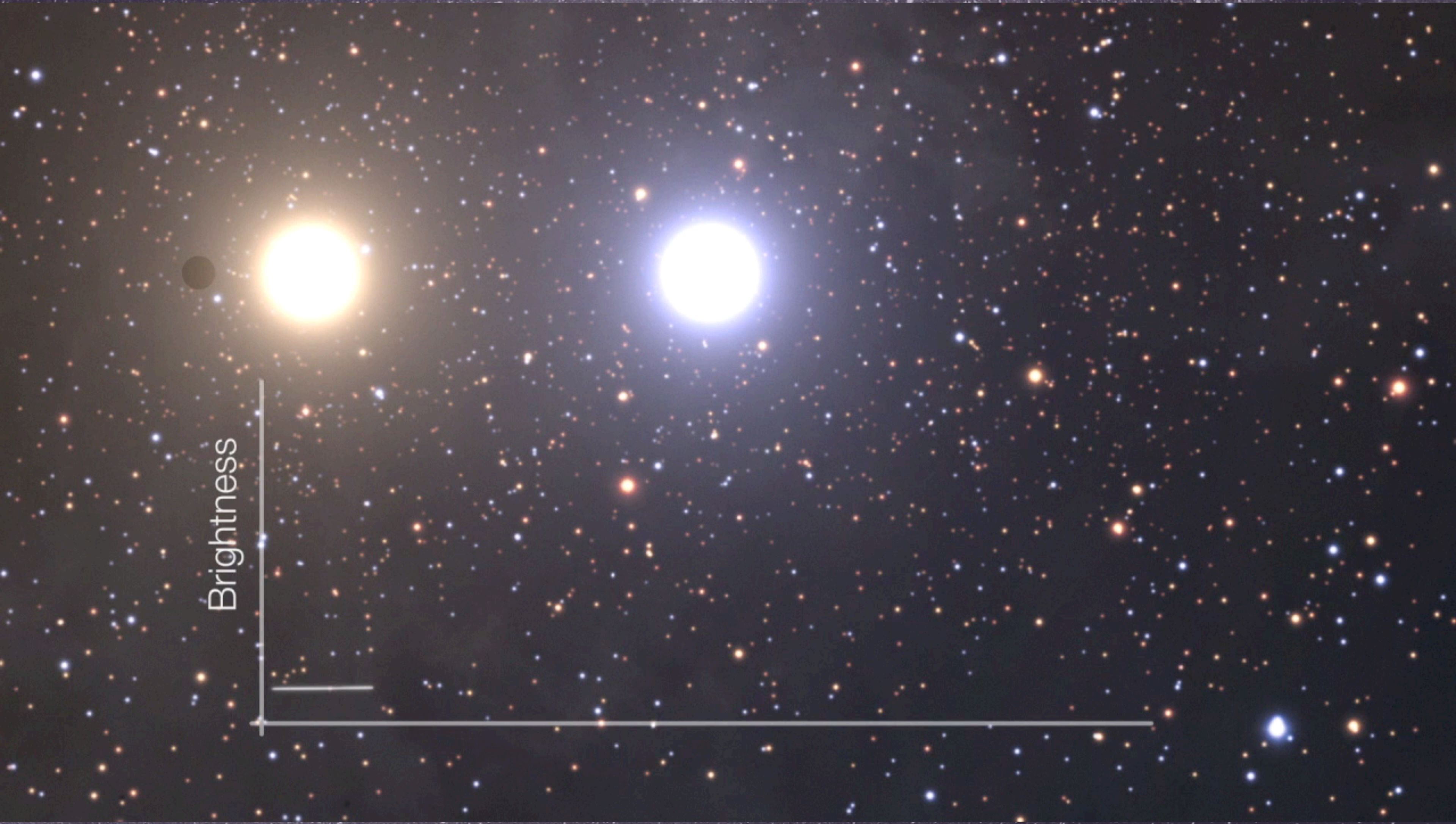
I. Basic Introduction to the Methodology and Theory of Microlensing Searches for Exoplanets
W, 21/Sept: Yossi Shvartzvald

II. Lens Companion Detection and Characterization
W, 28/Sept: Yossi Shvartzvald

III. Results from and Future Directions for Ground-based Microlensing Surveys
W, 12/Oct: Calen B. Henderson

IV. Results from and Future Directions for Space-based Microlensing Surveys
W, 2/Nov: Calen B. Henderson

Observational Microlensing

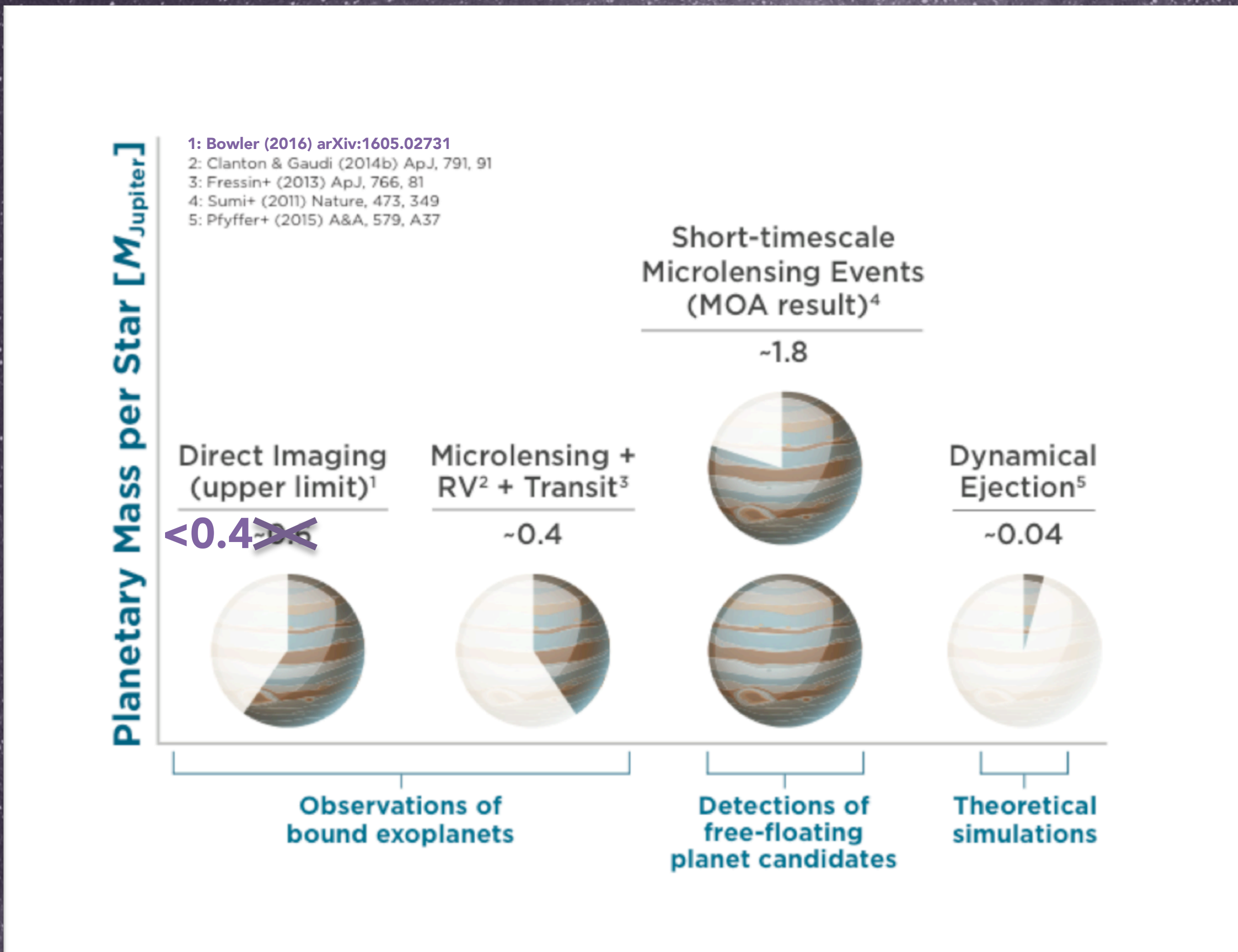


Science Goals: Quality versus Quantity

Addressing (relatively) Unexplored Demographic Questions

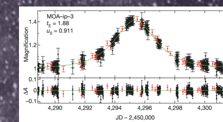
1. Free-floating planets
2. Galactic distribution
3. Cold and bound exoplanets

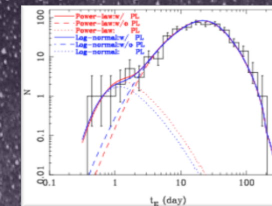
Planetary Mass Budget



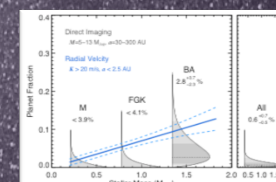
Henderson+ (2016), PASP, 128, 124401

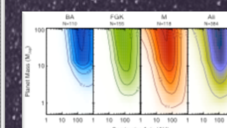
Microlensing (FFPs)



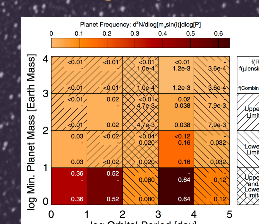


Direct Imaging

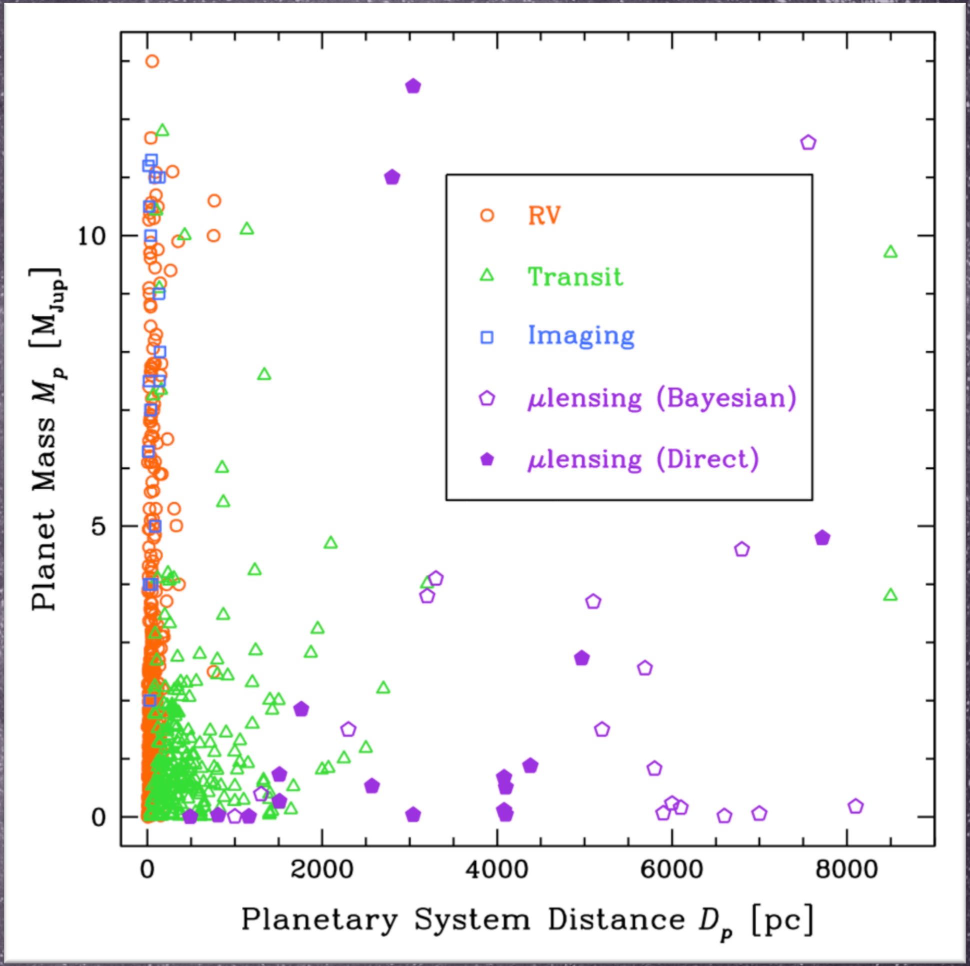




Transit + RV + Microlensing



Galactic Distribution of Exoplanets



Henderson+ (2016), PASP, 128, 124401

Why conduct microlensing from space?

Standard Observables

Single Object Lens

Einstein Timescale: t_E
(Finite Source Size: ρ)

Two-body Lens

Mass Ratio: q
Projected Separation: s

?

Parameters

Lens Mass: M_l
Lens System Distance: D_l

Why conduct microlensing from space?

Standard Observables

Single Object Lens

Two-body Lens

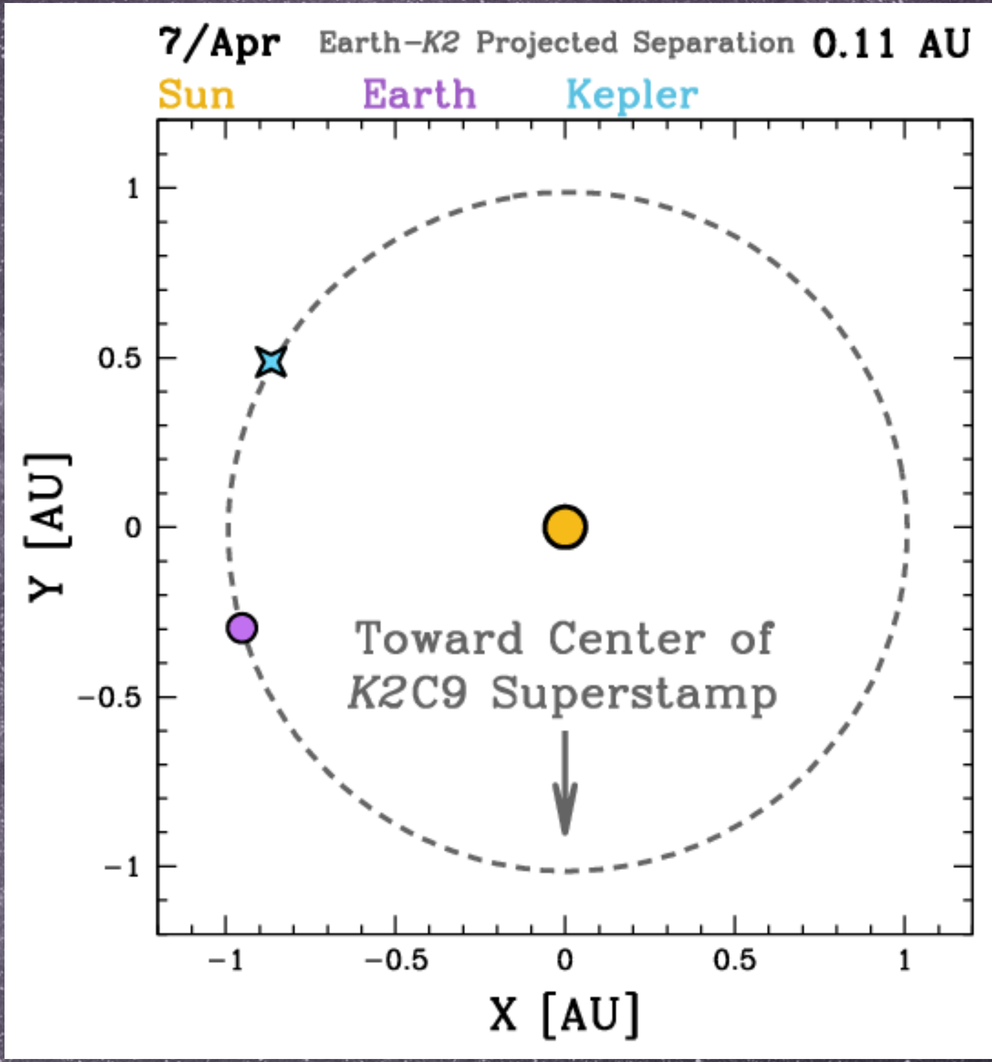
$$M_l = \theta_E / (\kappa \pi_E)$$

Parameters

Lens Mass: M_l

Lens System Distance: D_l

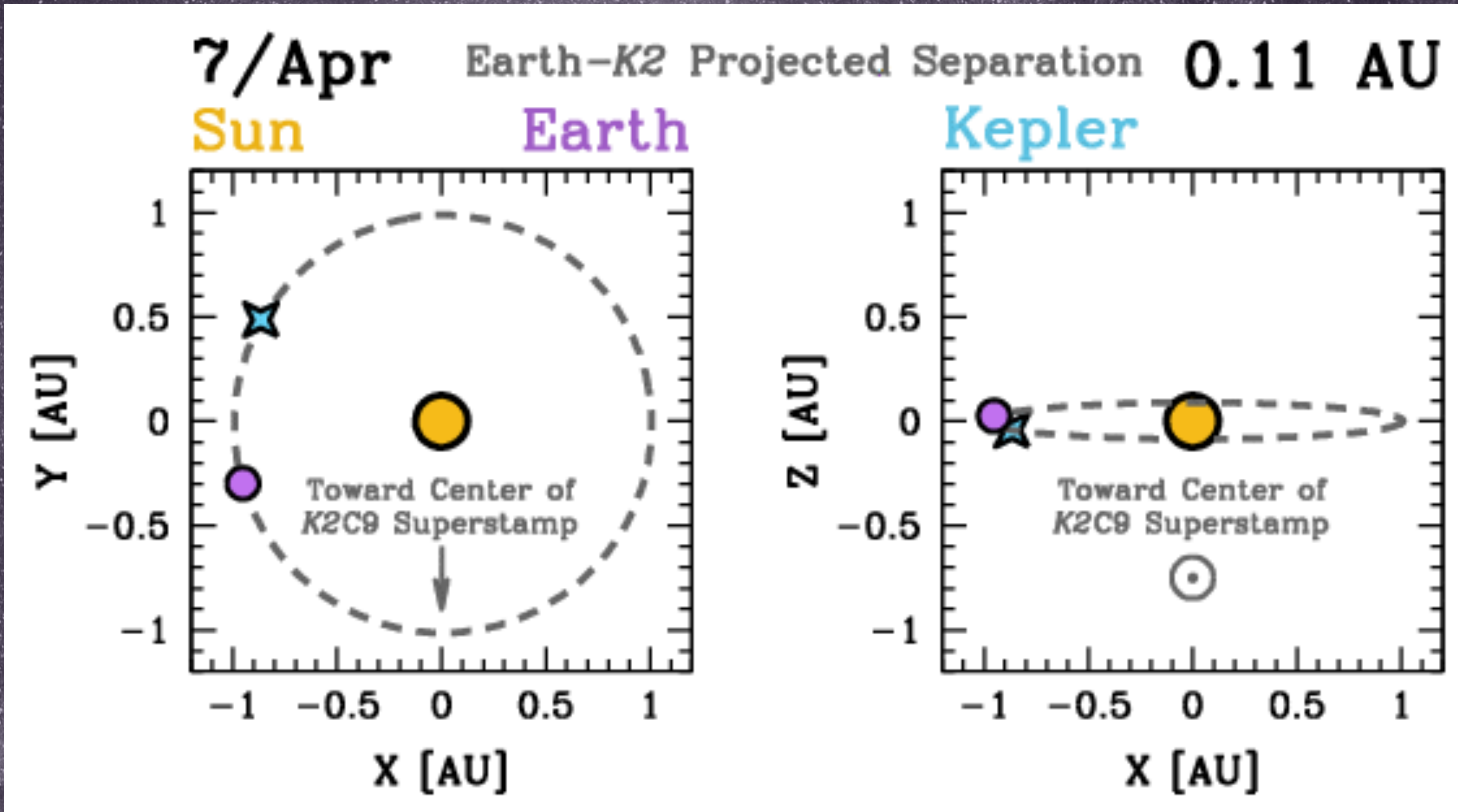
But what does satellite parallax *mean*?



Henderson+ (2016), PASP, 128, 124401

Found at:
http://www.astronomy.ohio-state.edu/~henderson/k2c9_parallax_animations/

But what does satellite parallax *mean*?



Henderson+ (2016), PASP, 128, 124401

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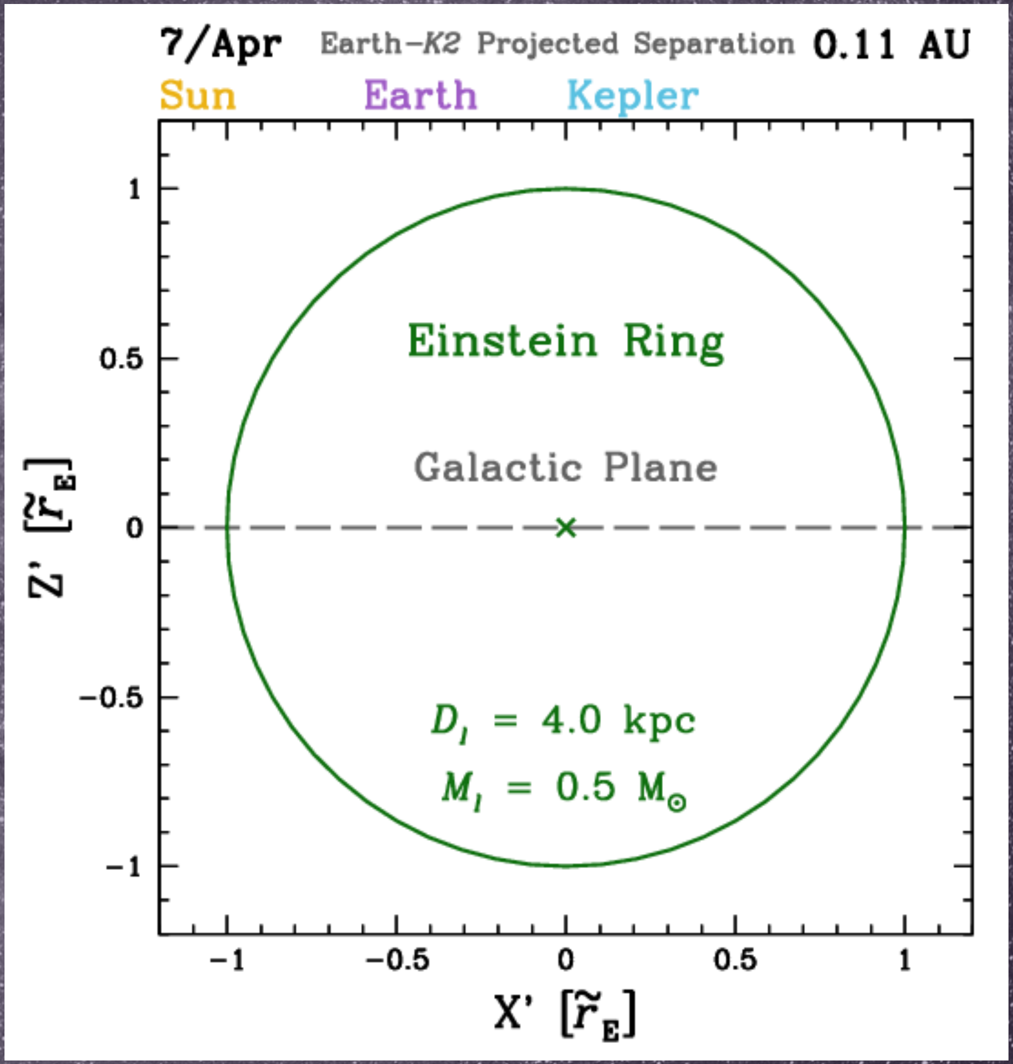

Henderson+ (2016), PASP, 128, 124401

Found at:
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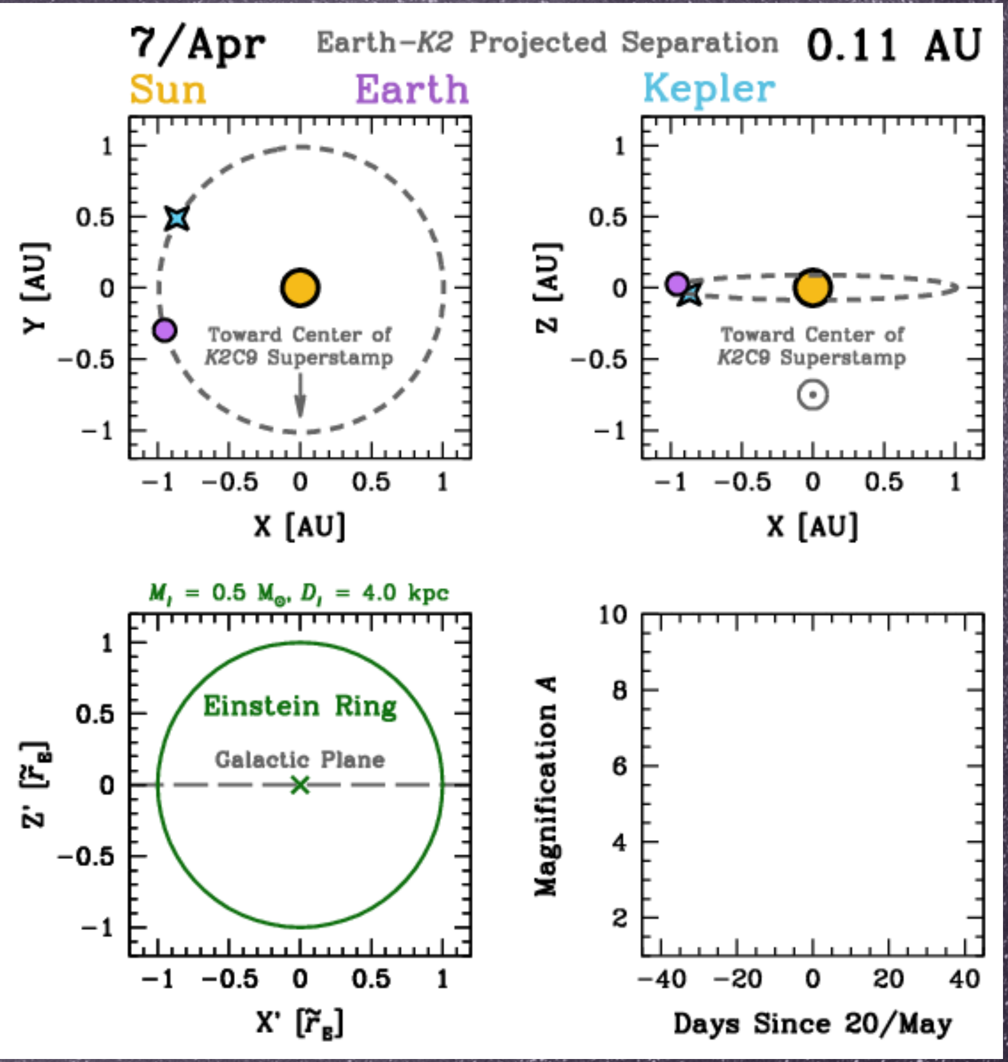
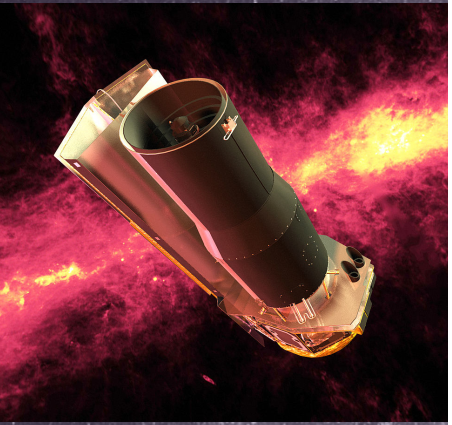


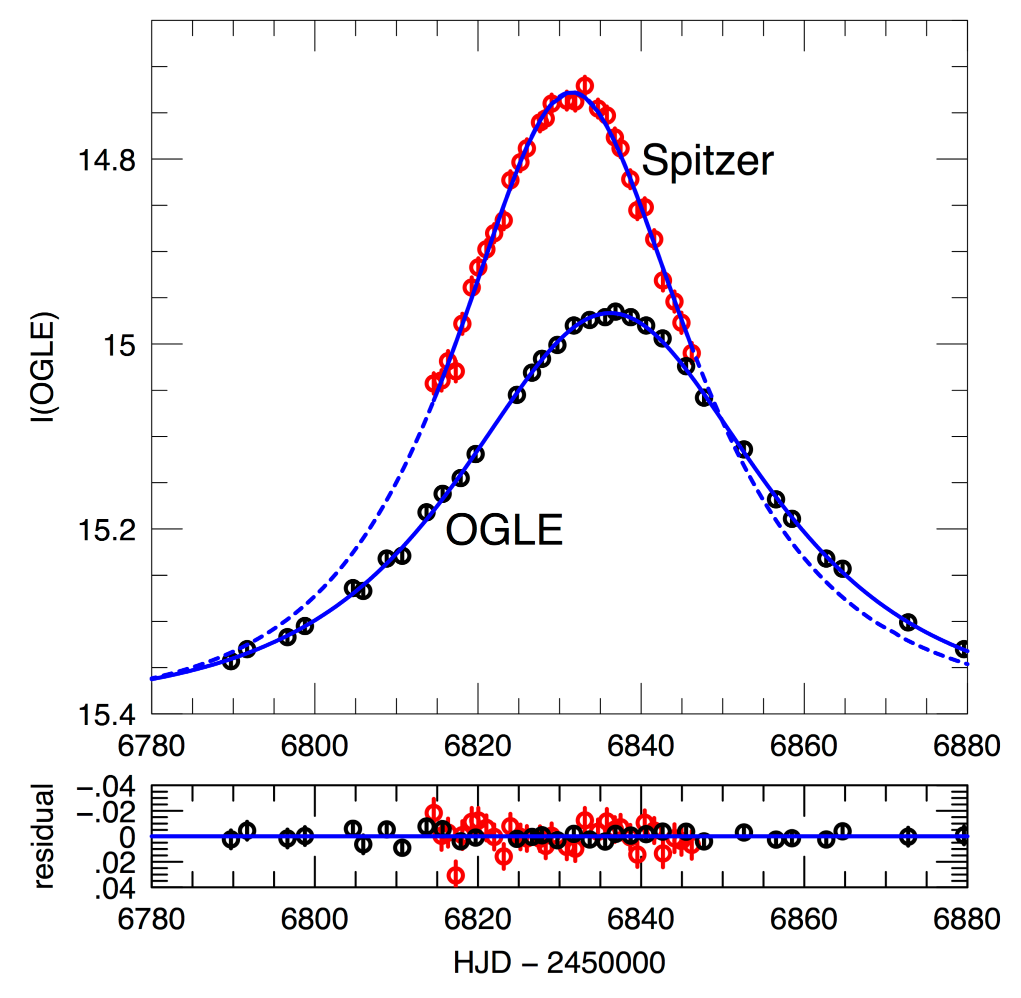
Henderson+ (2016), PASP, 128, 124401

Found at:
http://www.astronomy.ohio-state.edu/~henderson/k2c9_parallax_animations/

Microlens Parallax Satellite I. *Spitzer*

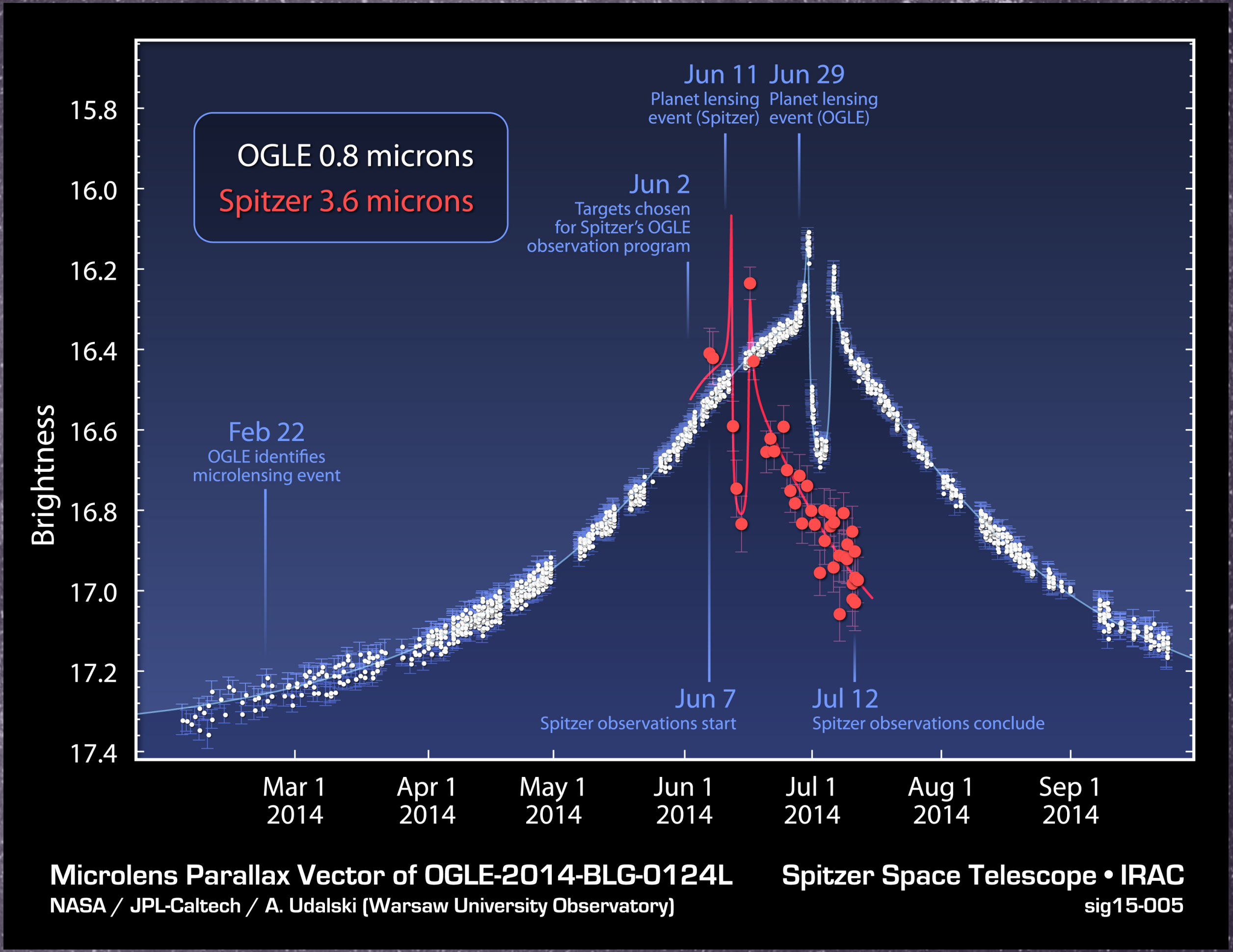


Credit: NASA/JPL-Caltech

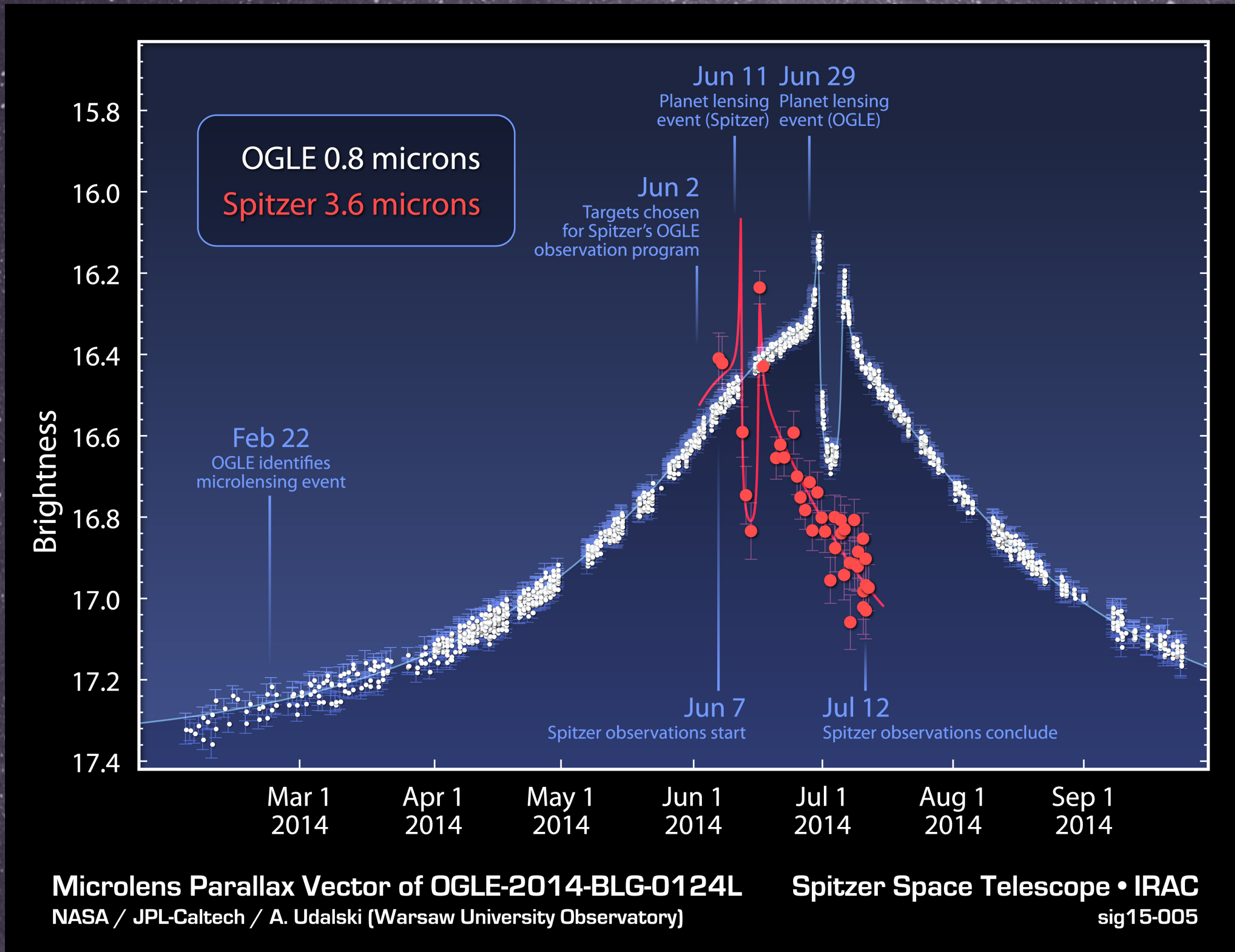


Credit: Krzysztof Ulaczyk

Microlens Parallax Satellite I. *Spitzer*



Microlens Parallax Satellite I. *Spitzer*



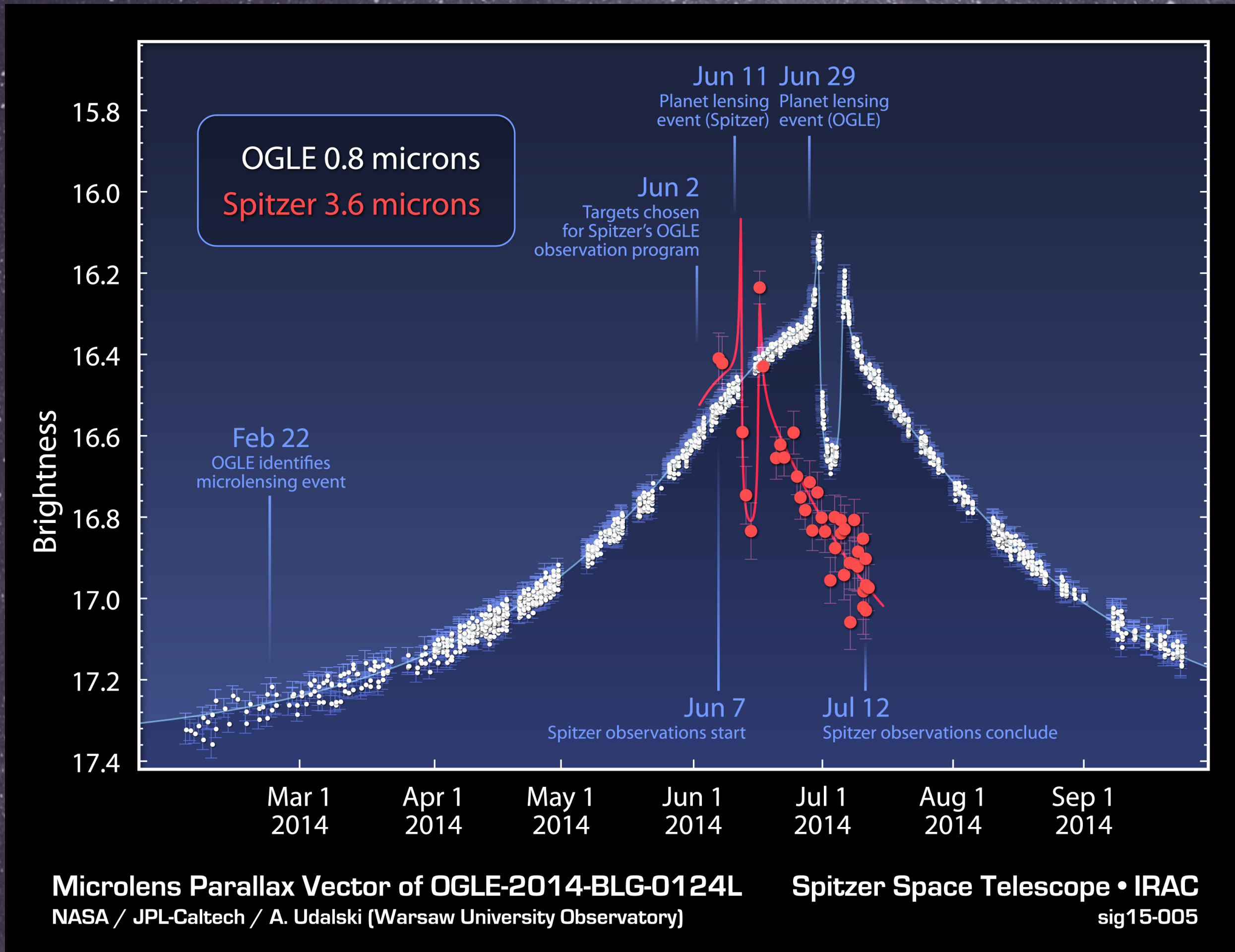
$M_p = 0.5\ M_J$

$M_* = 0.7\ M_\odot$

$D_l = 4.1$ kpc

$a_{inst,proj} = 3.1$ AU

Microlens Parallax Satellite I. *Spitzer*



$M_p = 0.5\ M_J$

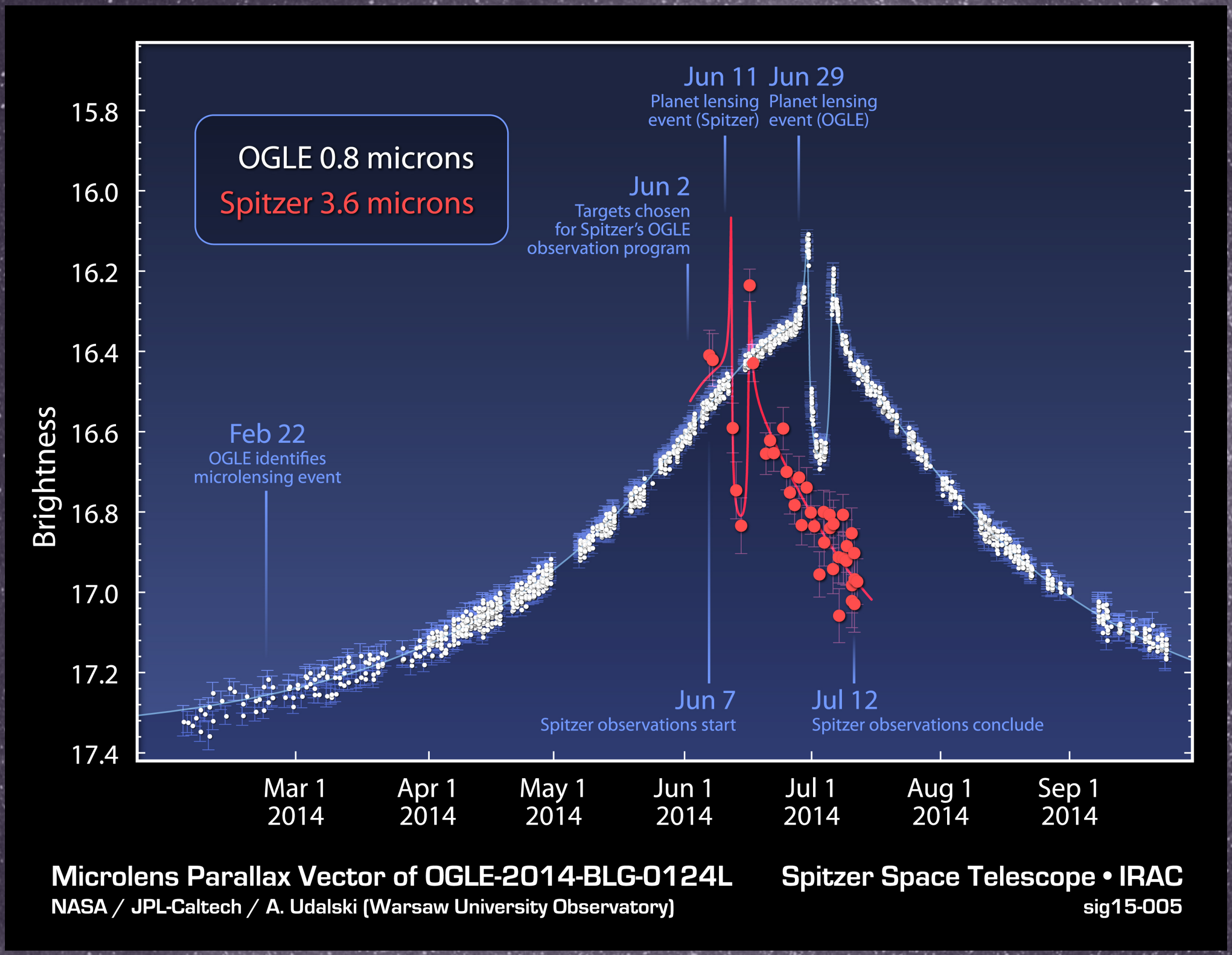
$M_* = 0.7\ M_\odot$

$D_l = 4.1$ kpc

$a_{inst,proj} = 3.1$ AU

σ_{π_E}(OGLE) $\approx$ 22%

Microlens Parallax Satellite I. *Spitzer*



$M_p = 0.5\ M_J$

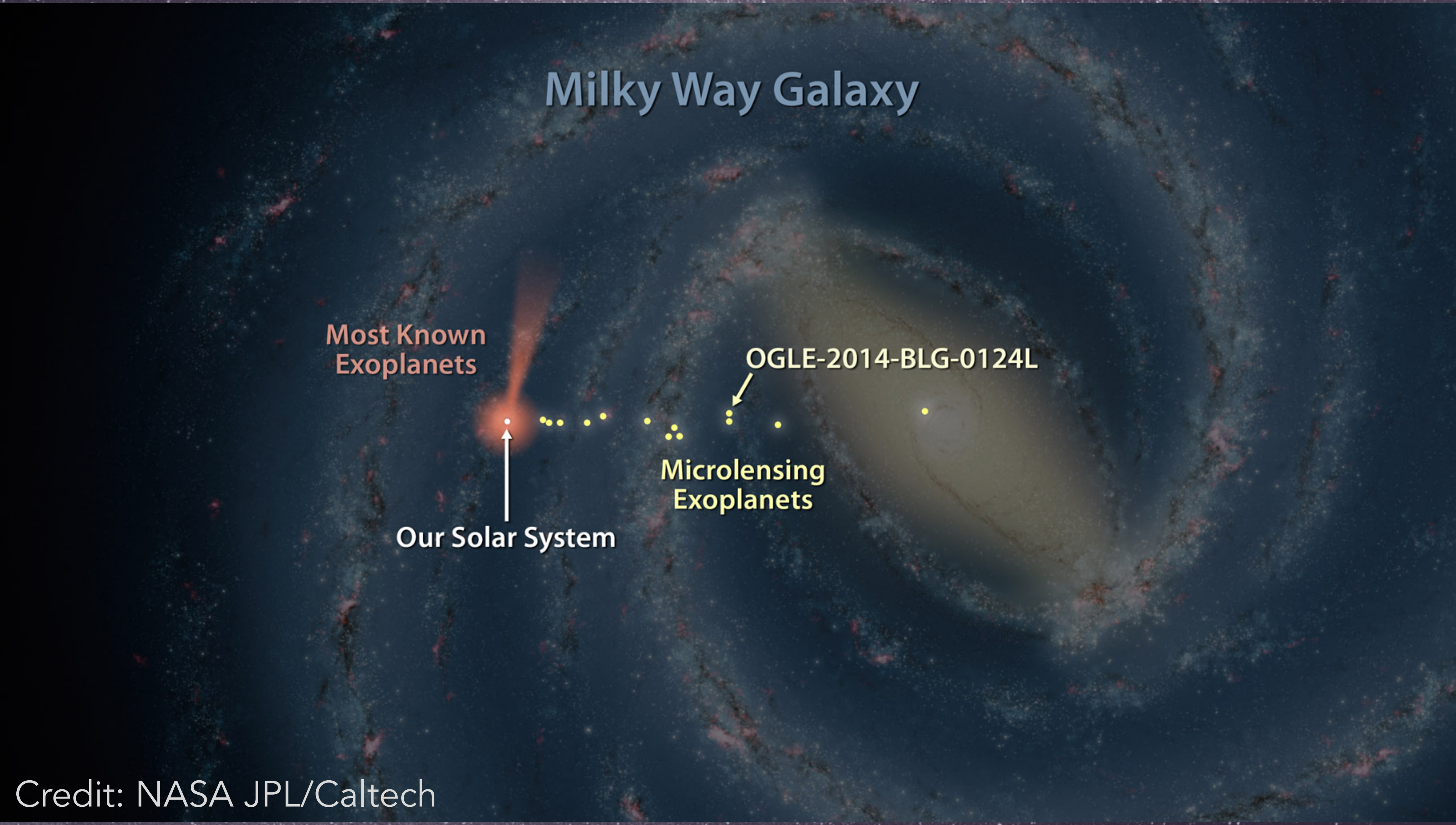
$M_* = 0.7\ M_\odot$

$D_l = 4.1$ kpc

$a_{\mathrm{inst,proj}} = 3.1$ AU

σ_{π_E}(OGLE) ≈ 22% σ_{π_E}(*Spitzer*) ≈ 2.5%

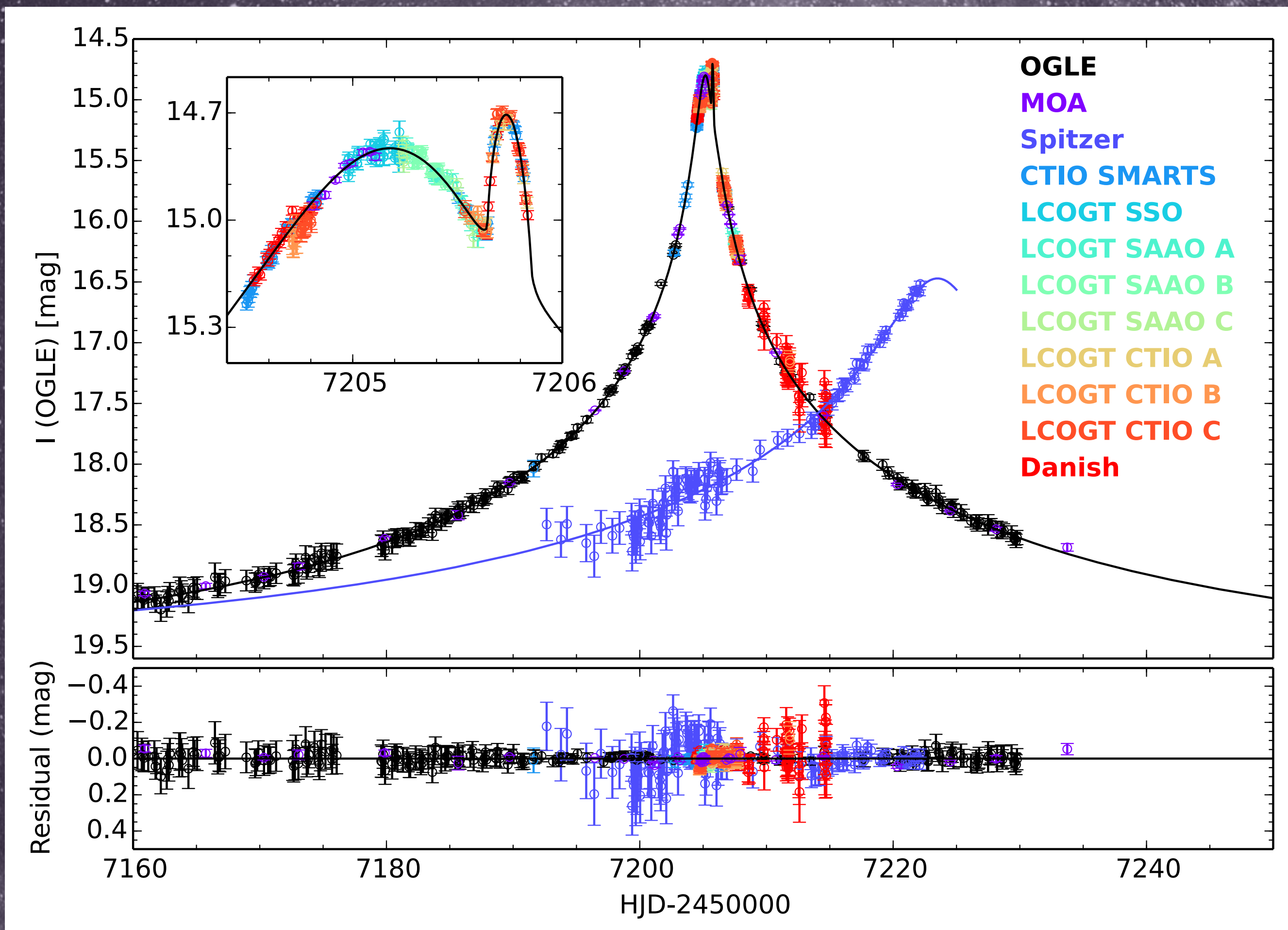
Galactic Distribution of Exoplanets



Credit: NASA JPL/Caltech

Microlens Parallax Satellite I. *Spitzer*

OGLE-2015-BLG-0966



$M_p \approx 21\ M_{Earth}$

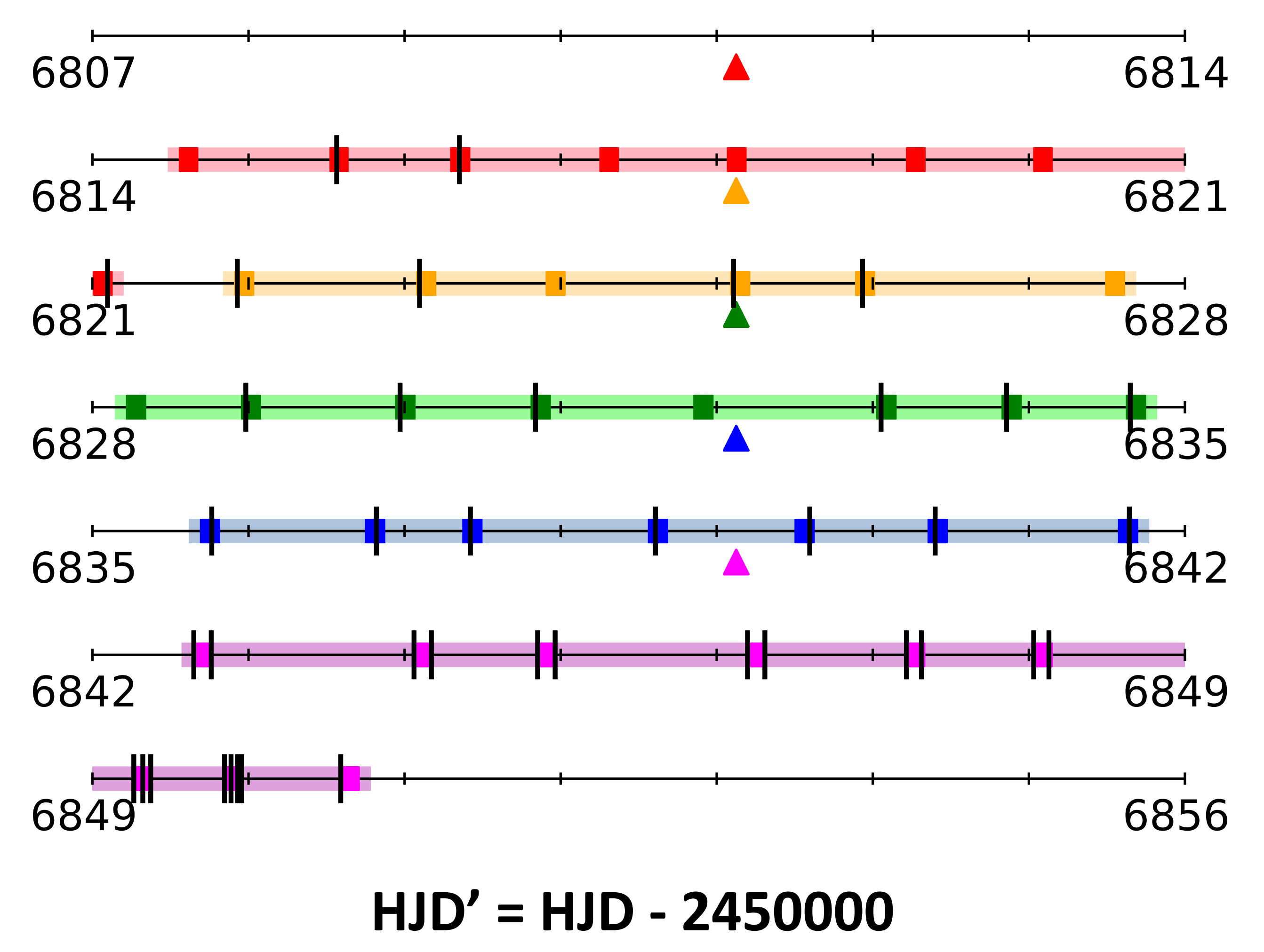
$M_* \approx 0.38\ M_\odot$

$D_l \approx 3$ kpc

[$\sigma \approx 10\%$]

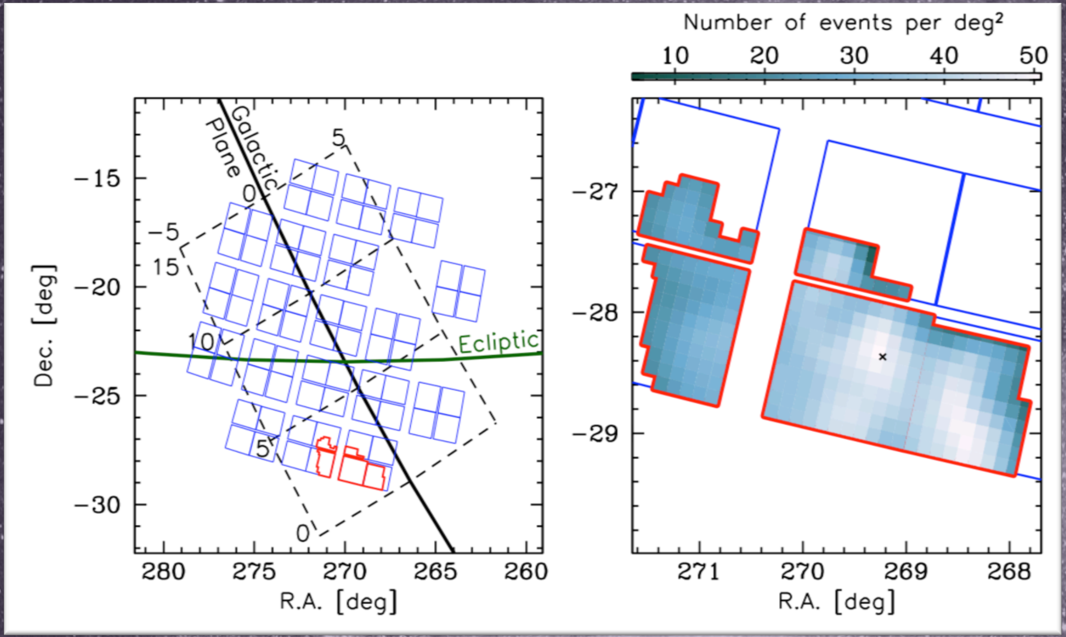
Street+ (2016), ApJ, 819, 93

Limitations of *Spitzer* Campaigns



Udalski+ (2015) ApJ, 799, 237

Enter *K2's* Campaign 9



Area*	3.74 deg^2
Cadence	30 min
Events*	106 (expected)
Start	22/April, 14:04 UT
End	2/July, 22:34 UT
Duration	71.4 days

Found in Henderson+ (2016), PASP, 128, 124401

Uses methodology of Poleski (2016) MNRAS, 455, 3656

* Postage stamps added later to C9a (34) & C9b (61) target lists for ongoing events (70 unique)

Key Contributors to *K2C9*

Microlensing Science Team

David Bennett
Senior Research Scientist
NASA Goddard

Scott Gaudi
Professor of Astronomy, Thomas Jefferson Chair
The Ohio State University, JPL

Calen B. Henderson
NASA fellow
JPL/Caltech

David W. Hogg
Professor of Physics and Data Science
New York University

Matthew Penny
Sagan Fellow
The Ohio State University

Radek Poleski
Research Associate
The Ohio State University

Rachel Street
Project Scientist
Las Cumbres Observatory Global Telescope

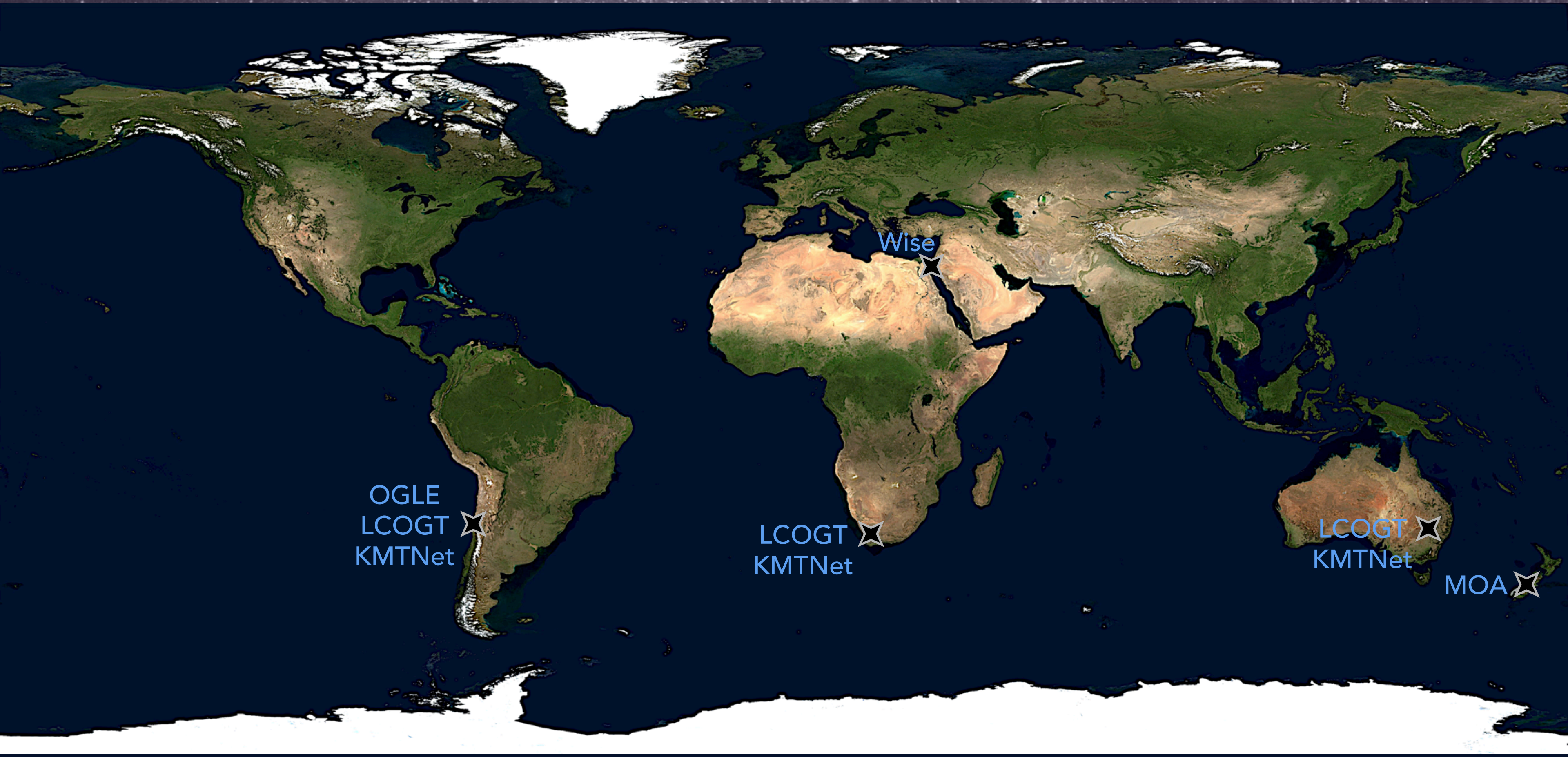
K2 Project Office

Tom Barclay
K2 Guest Observer Office Director
NASA Ames

Geert Barentsen
K2 Guest Observer Office
NASA Ames

Steve Howell
Project Scientist
NASA Ames

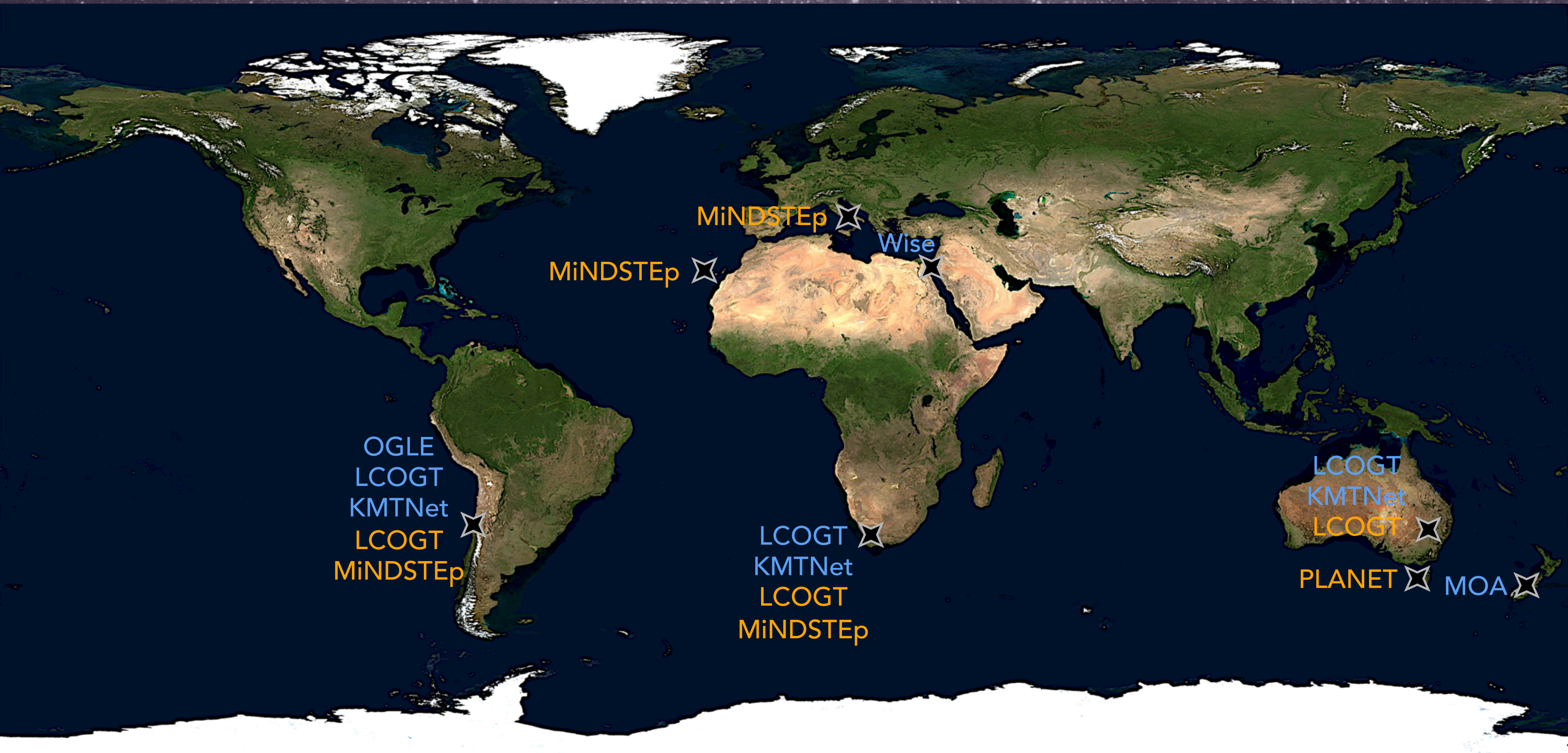
Simultaneous Ground-based Resources



Automated Survey

Henderson+ (2016), PASP, 128, 124401

Simultaneous Ground-based Resources

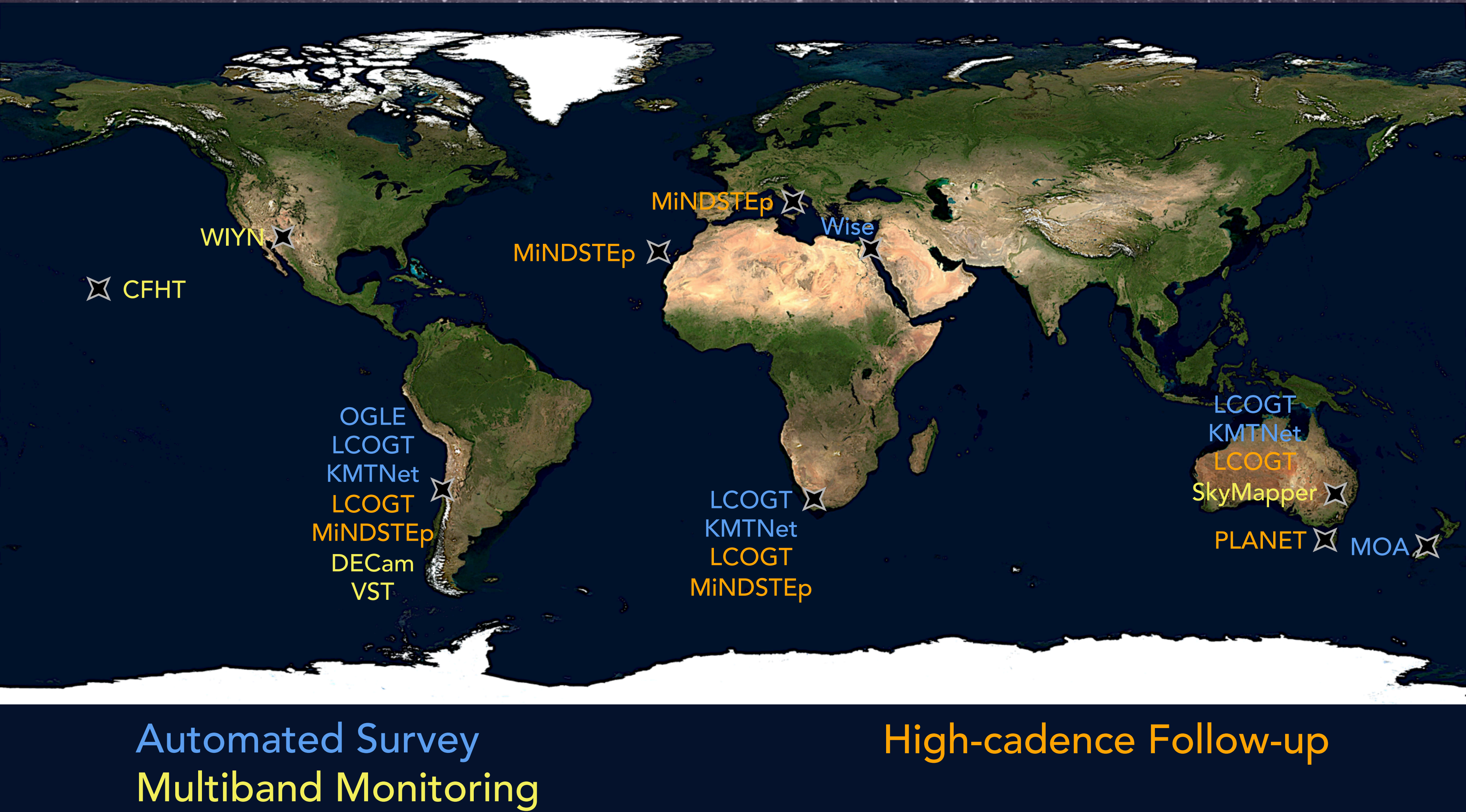


Automated Survey

High-cadence Follow-up

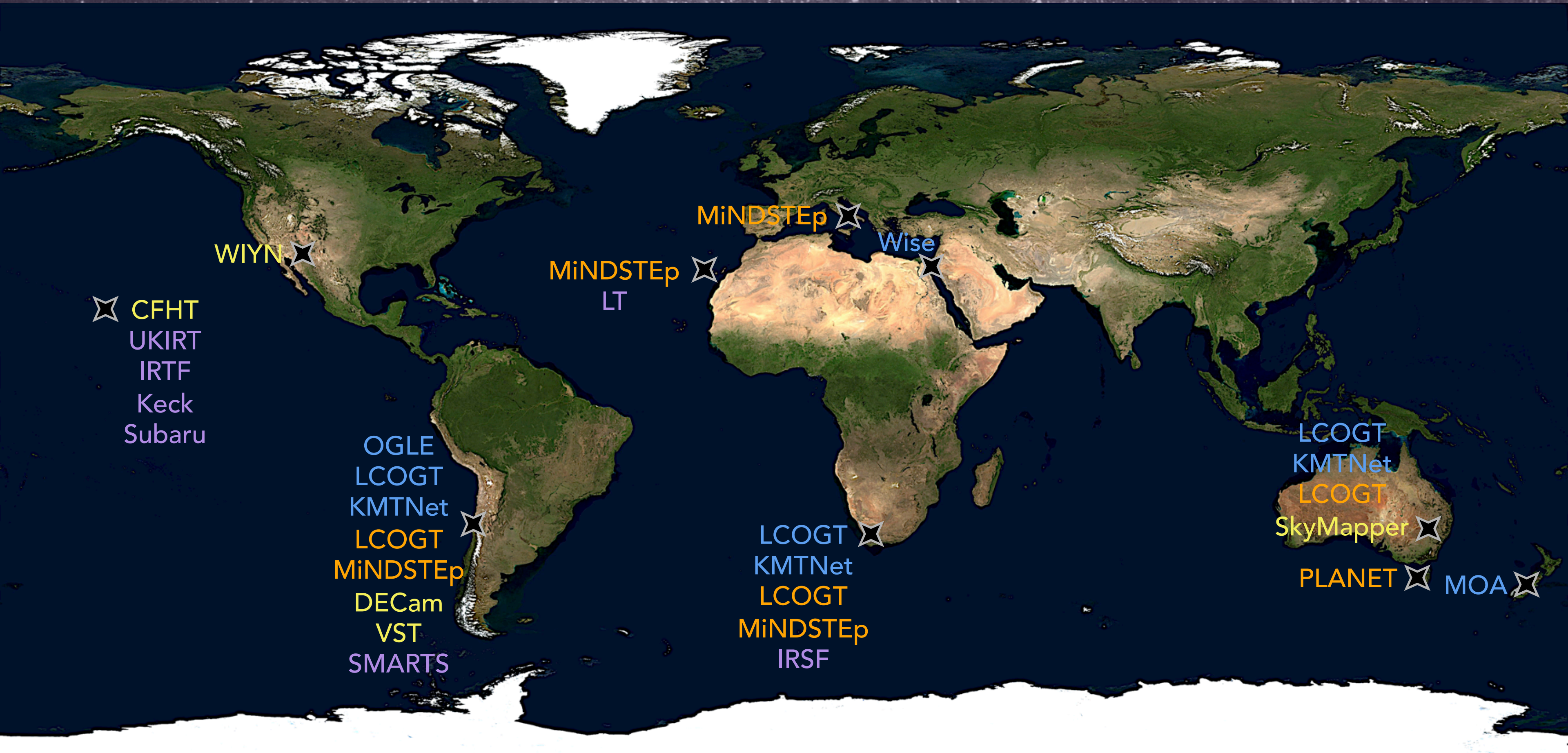
Henderson+ (2016), PASP, 128, 124401

Simultaneous Ground-based Resources



Henderson+ (2016), PASP, 128, 124401

Simultaneous Ground-based Resources



Automated Survey
Multiband Monitoring

High-cadence Follow-up
Near-infrared Source Fluxes

Henderson+ (2016), PASP, 128, 124401

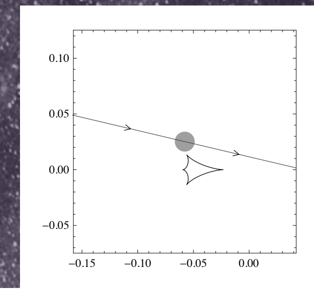
Preliminary *K2C9* Parallax Inventory

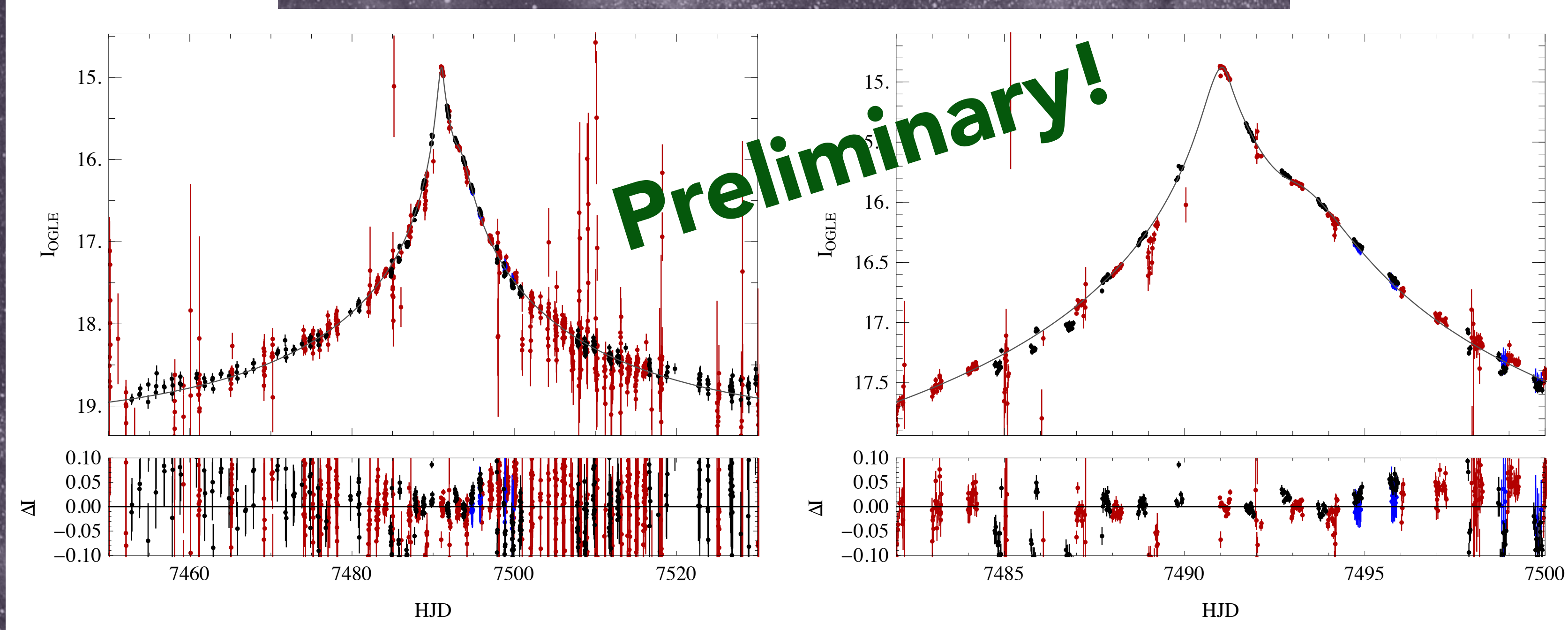
Total events	109 (179)
Bound Planets	3
FFP Candidates	9
Stellar Binaries	8
Long-timescale	13

Values are, generally, lower limits!!

Bound Planetary Candidate!

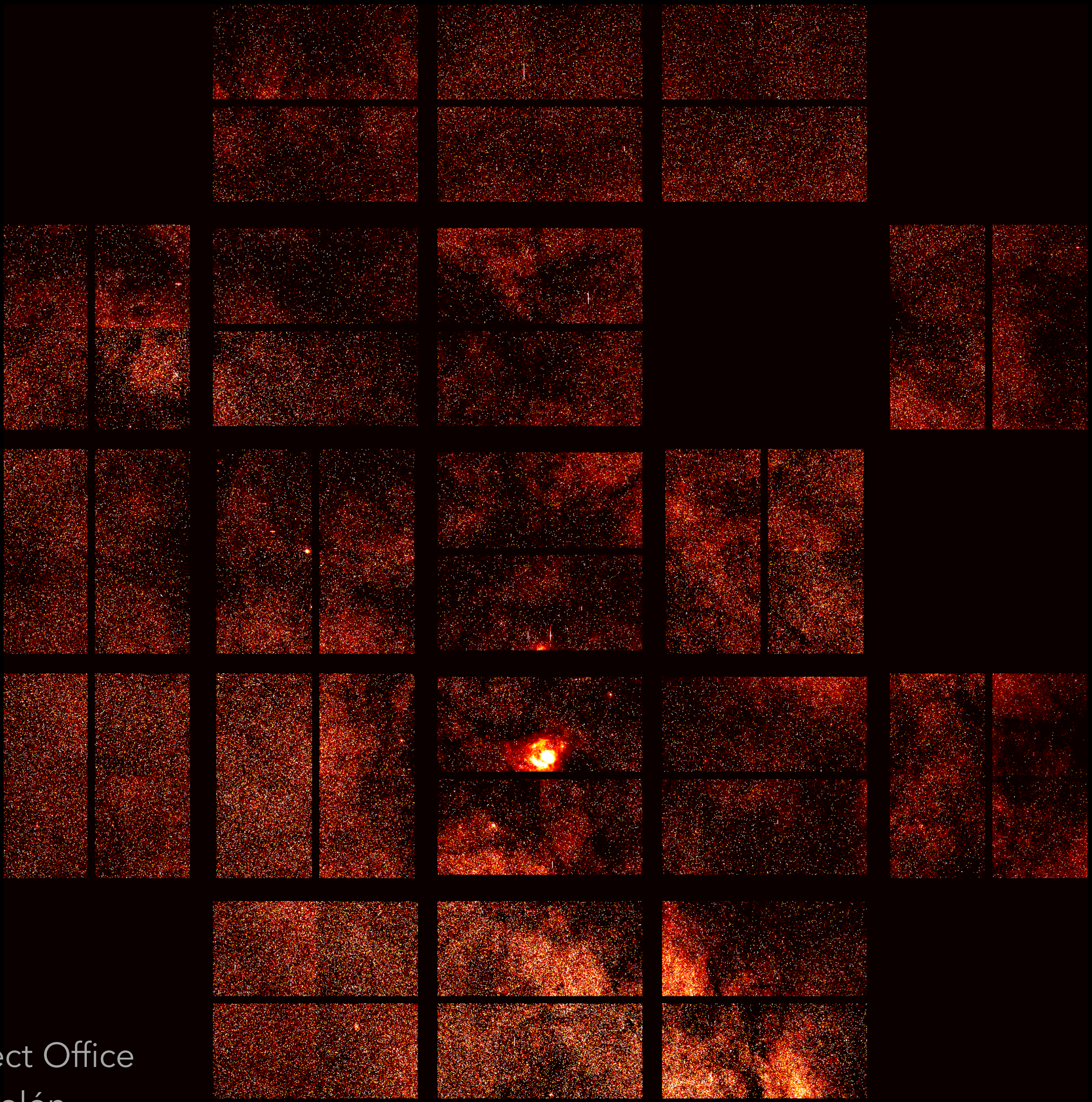
$$q = \frac{M_p}{M_*} \sim 0.03$$



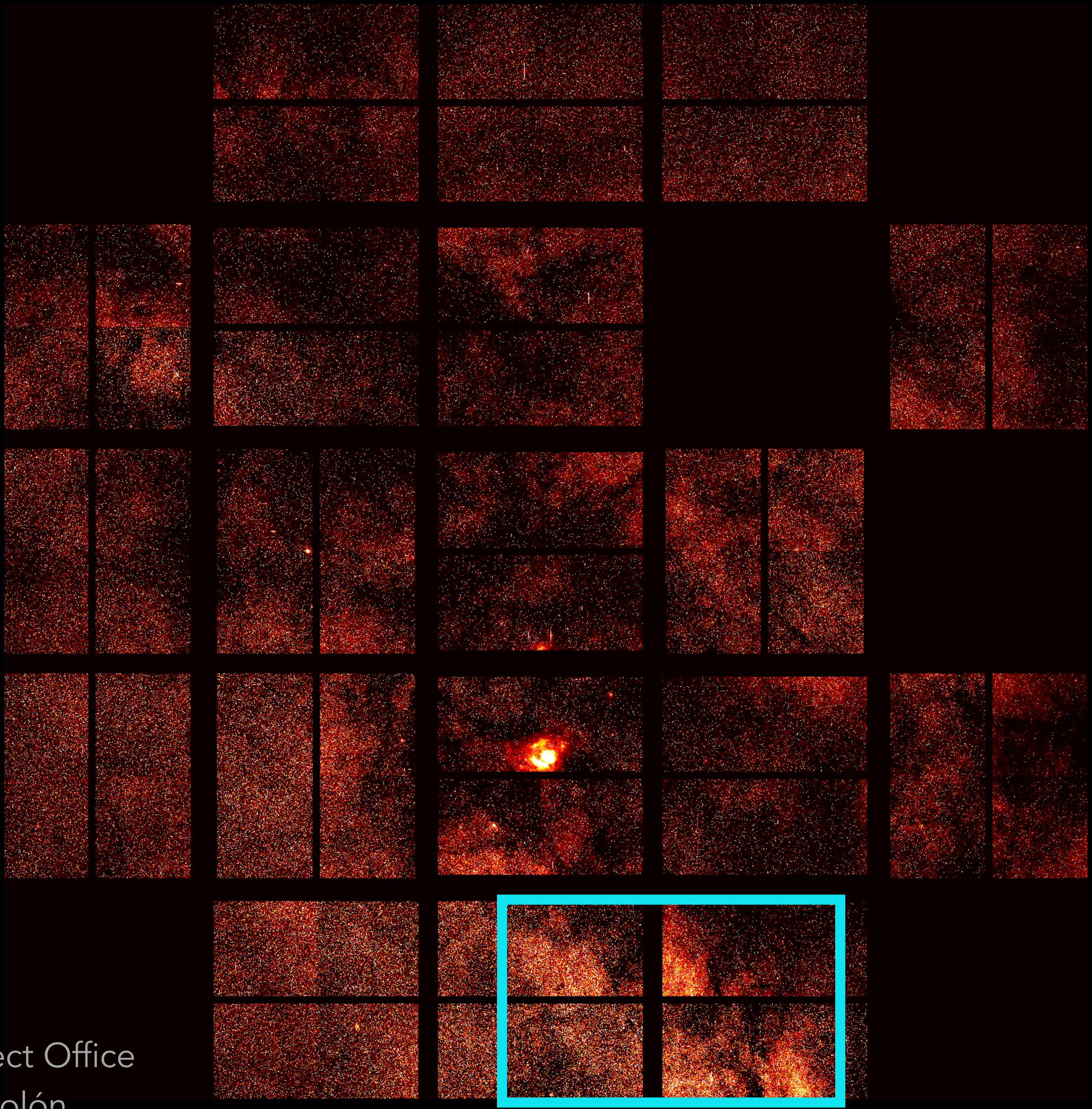


From Valerio Bozza's real-time modeling:

http://www.fisica.unisa.it/GravitationAstrophysics/RTModel.htm



From *K2* Project Office
Courtesy K. Colón



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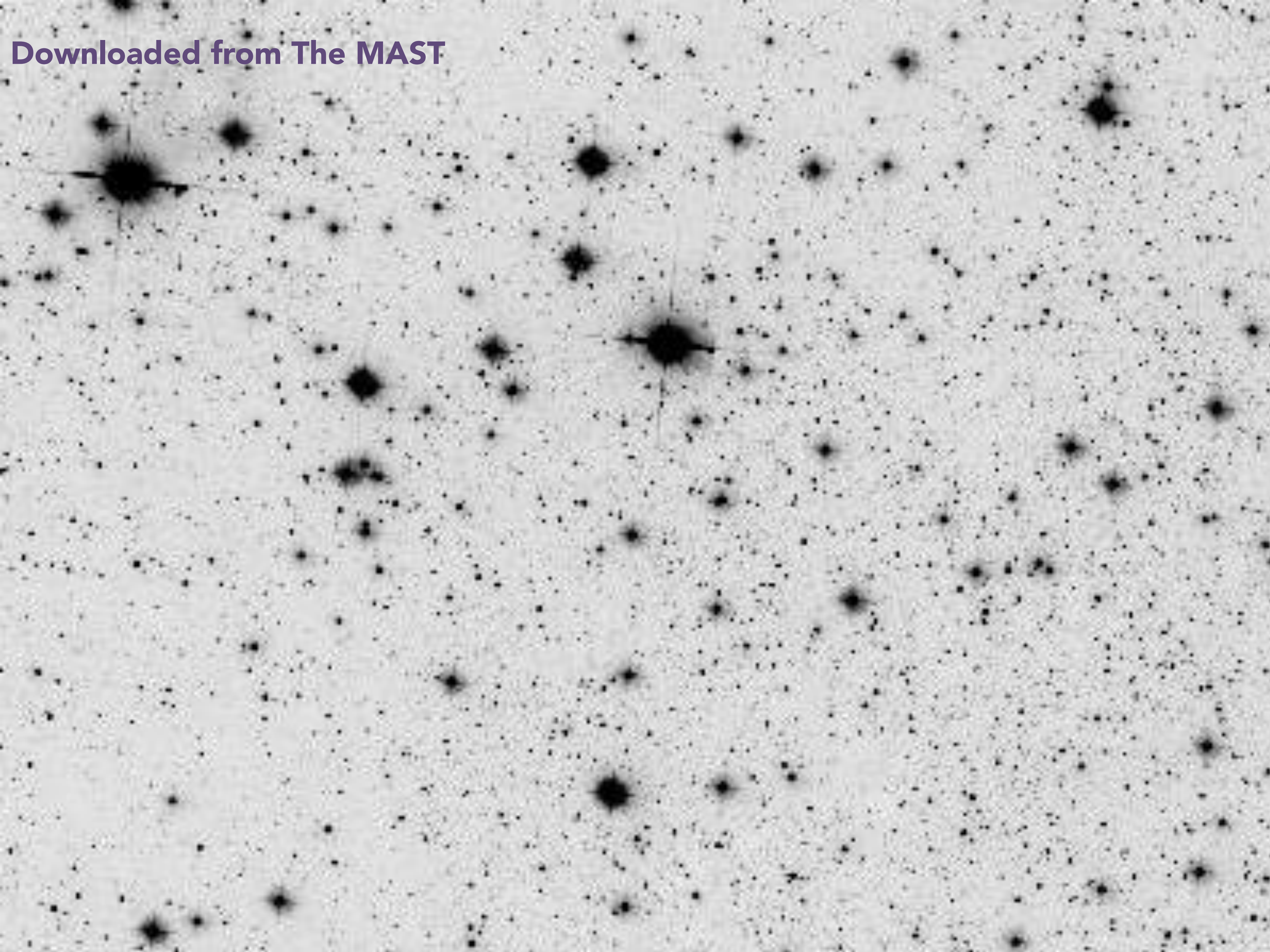
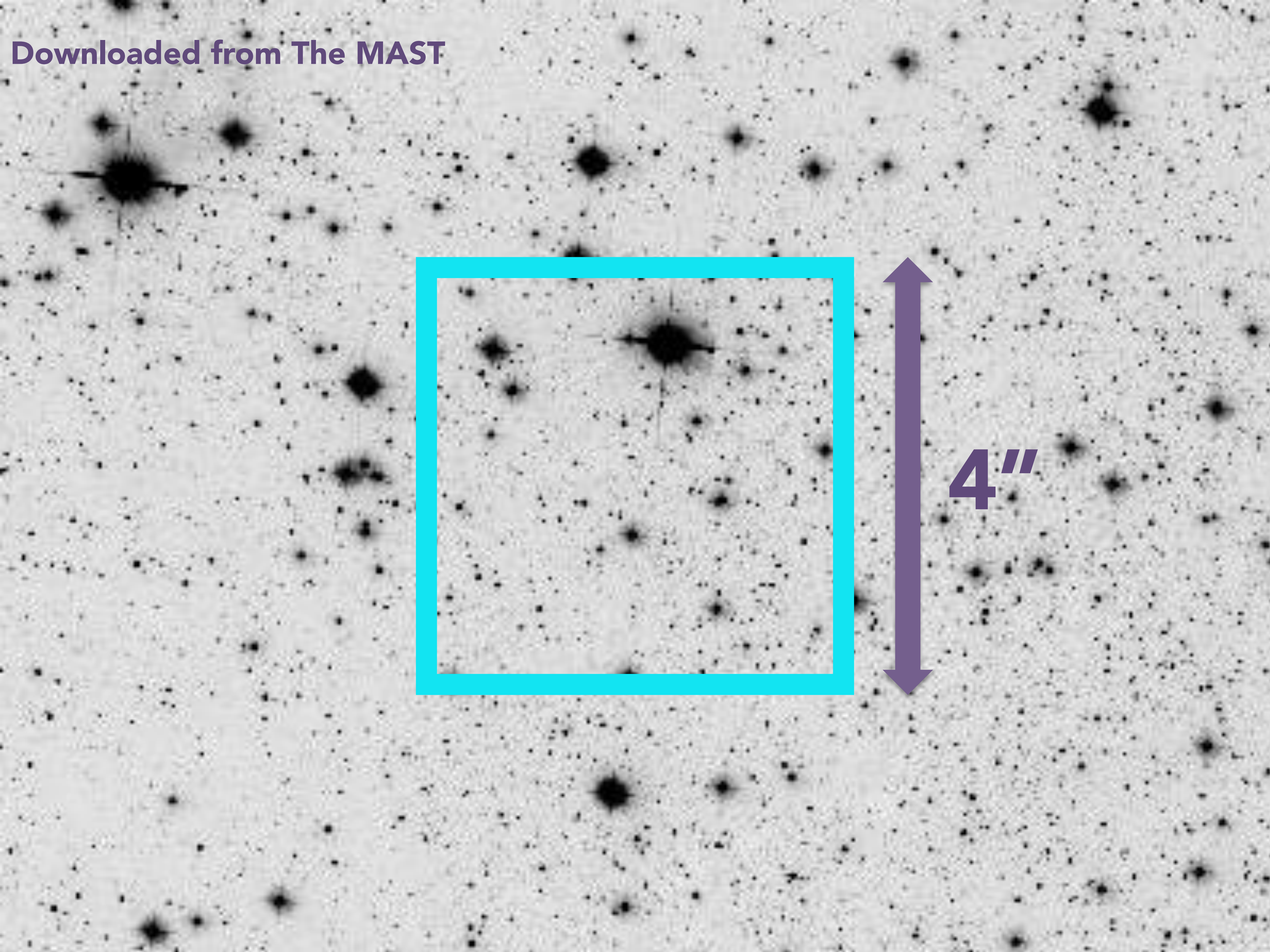
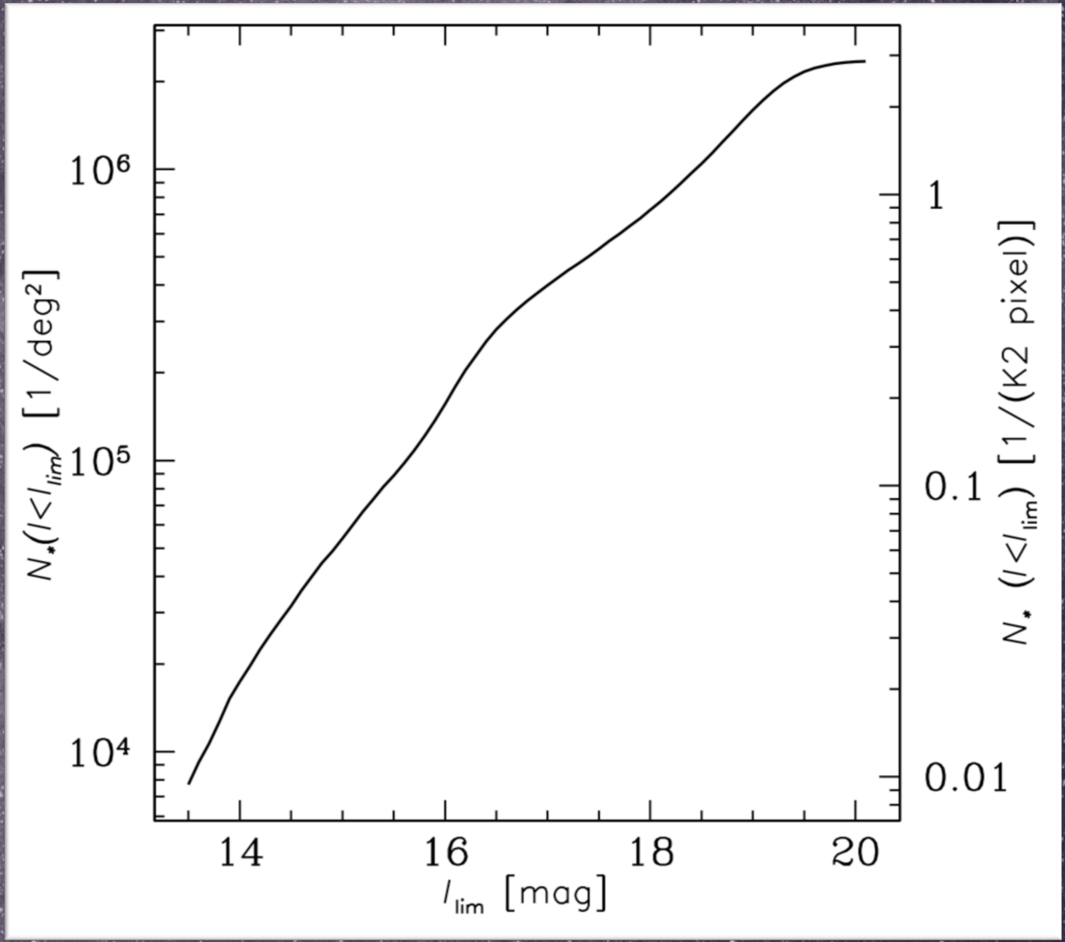
Courtesy K. Colón

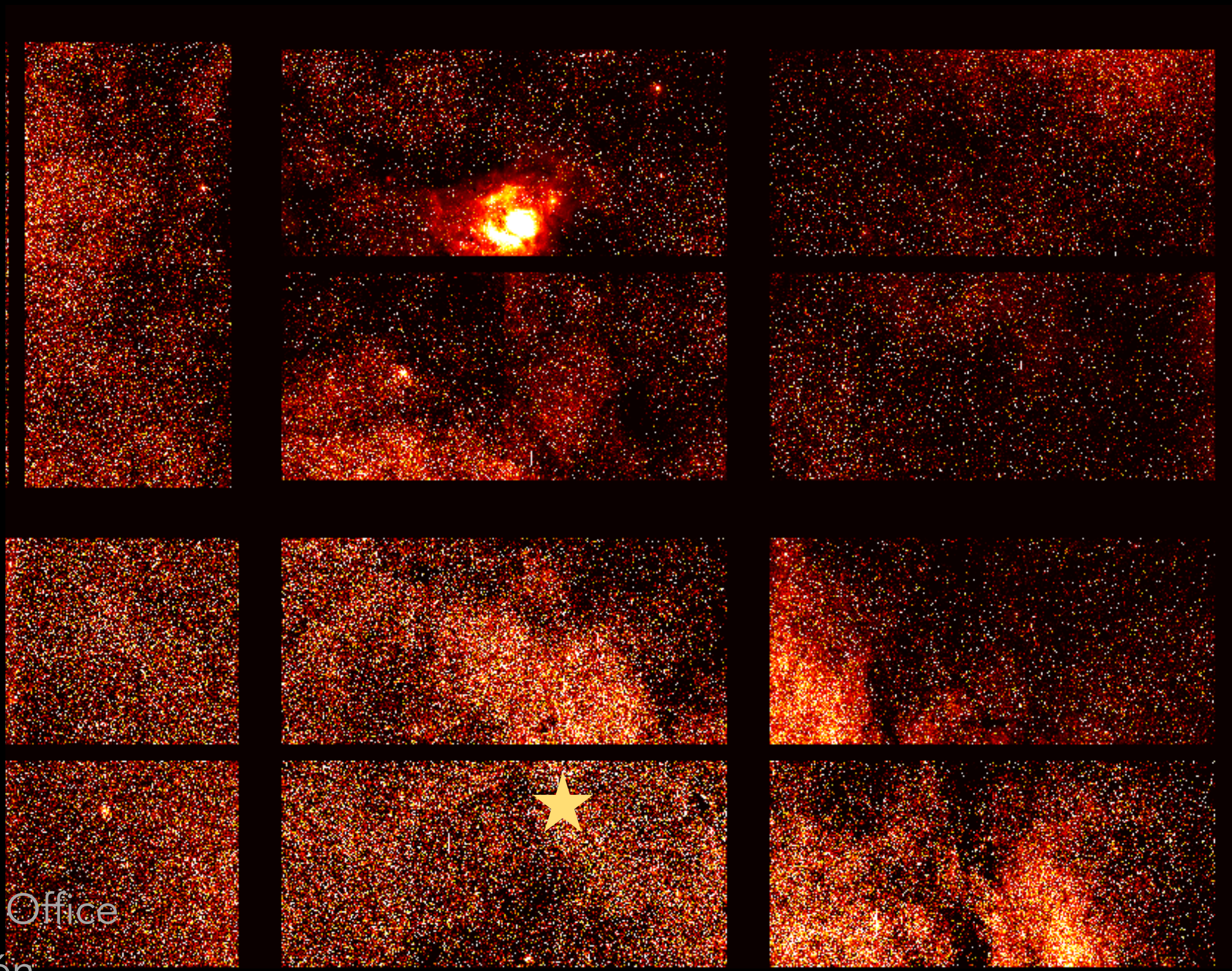



Downloaded from The MAST
4″

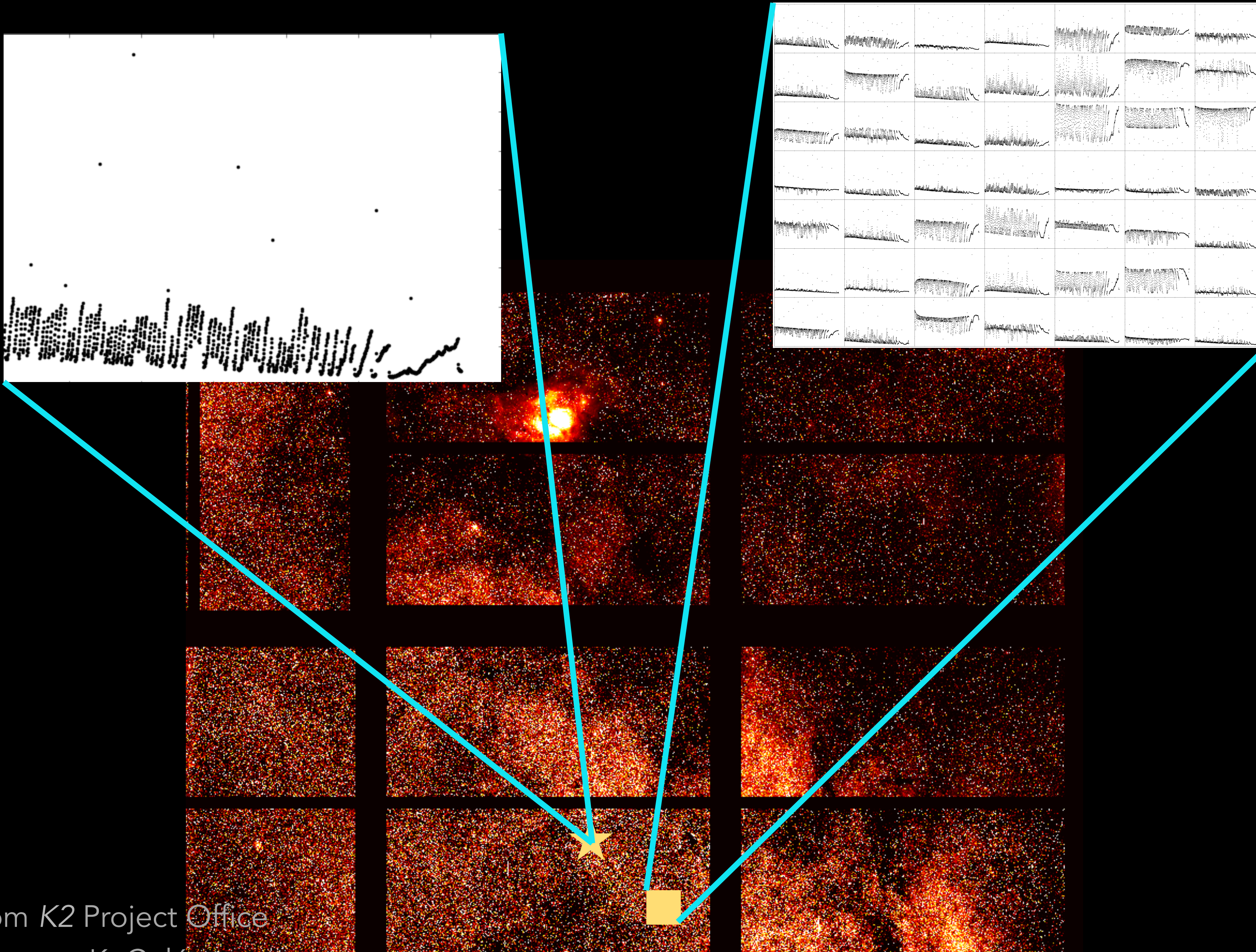
Moving Forward – Photometry Challenges: Blending in *Kepler*



Henderson+ (2016), PASP, 128, 124401



From *K2* Project Office
Courtesy K. Colón

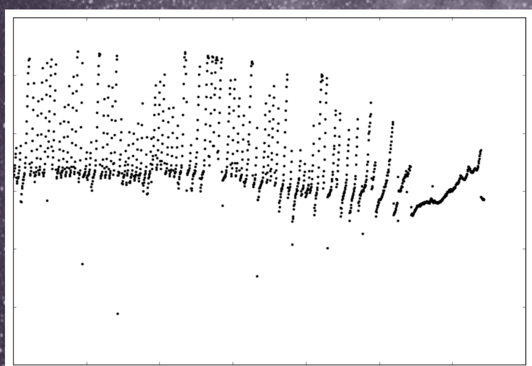


From *K2* Project Office
Courtesy K. Colón

Moving Forward – Photometry Challenges: *Kepler* Event Recovery

Input pixels

Causal Pixel Model



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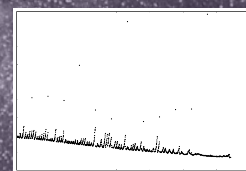

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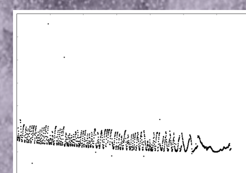

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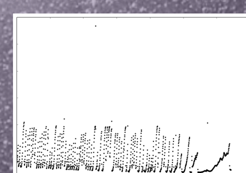

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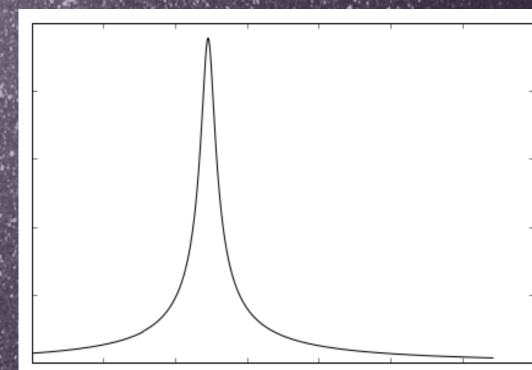
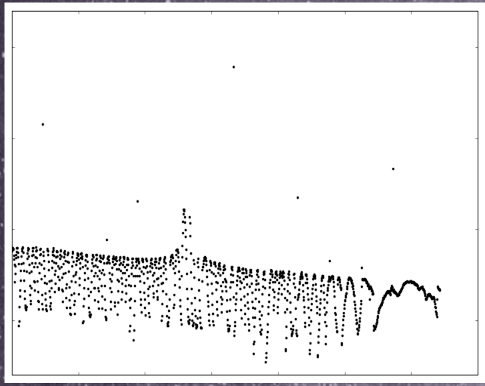
Microlensing Model

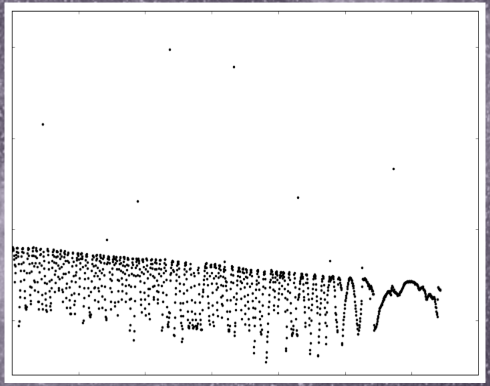


Moving Forward – Photometry Challenges: *Kepler* Event Recovery

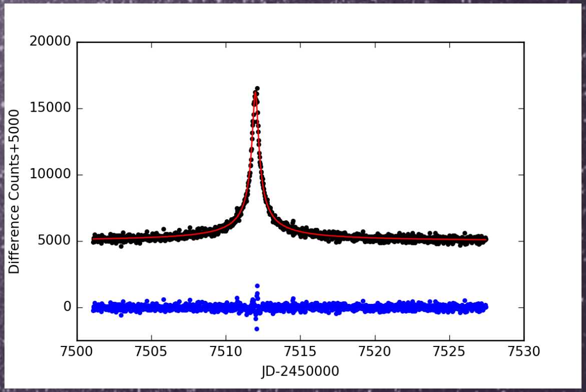
Raw Pixel Light Curve
(i.e., data!)



Causal Pixel Model



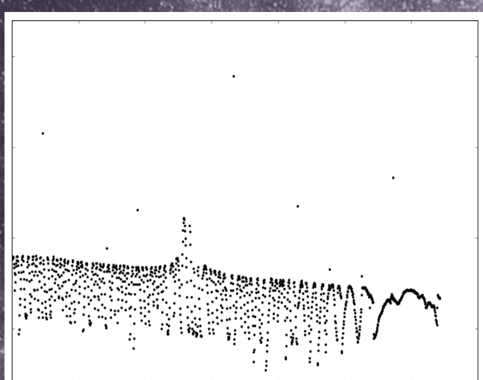
Output light curve!



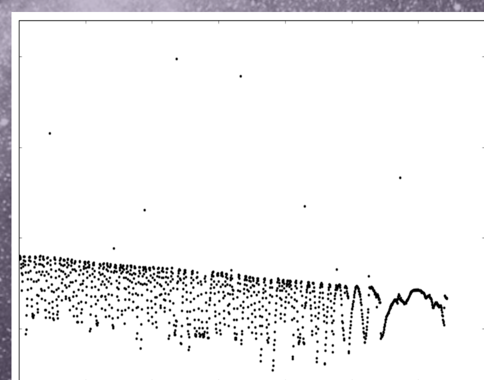
Moving Forward – Photometry Challenges: *Kepler* Event Recovery

Dun Wang
Graduate Student, NYU

Raw Pixel Light Curve
(i.e., data!)



Causal Pixel Model



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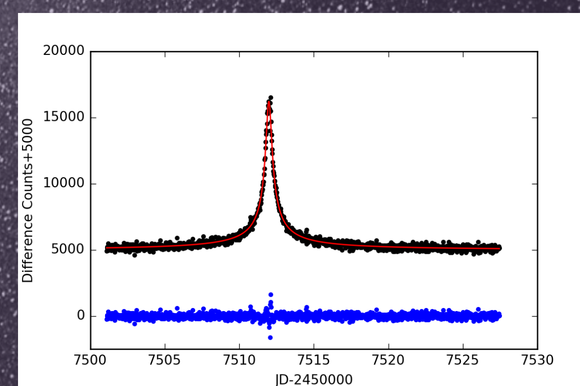
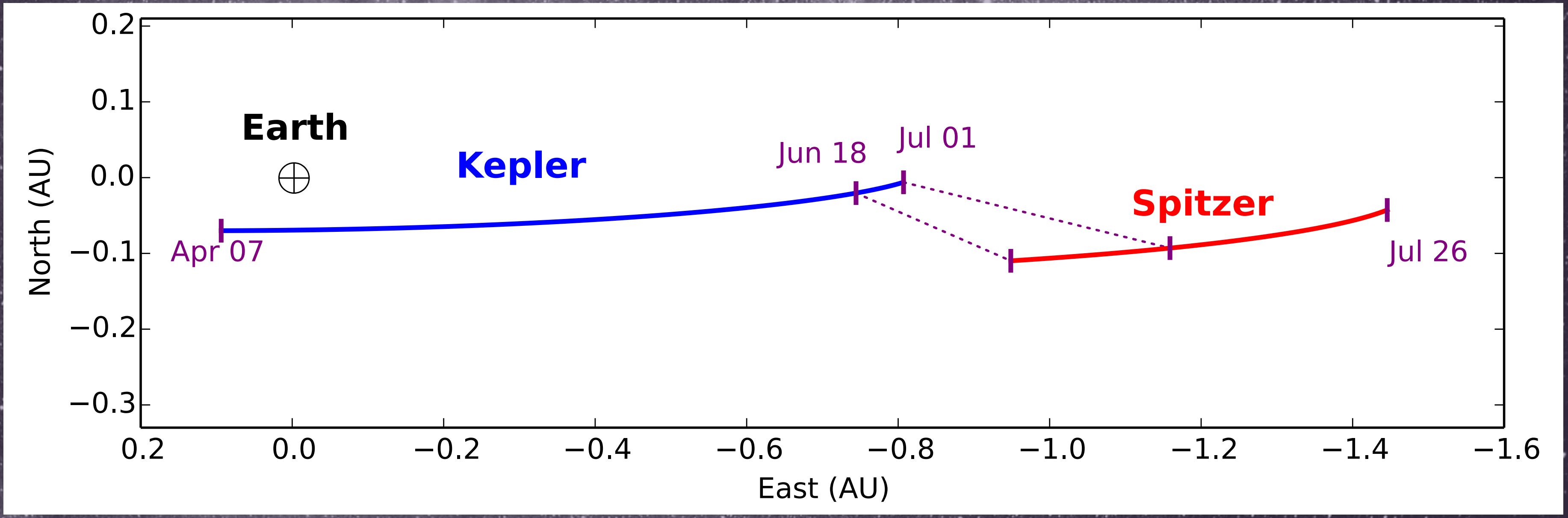


Moving Forward:
K2C9 Synergies

1 *Spitzer*



Henderson+ (2016), PASP, 128, 124401

Moving Forward:
K2C9 Synergies

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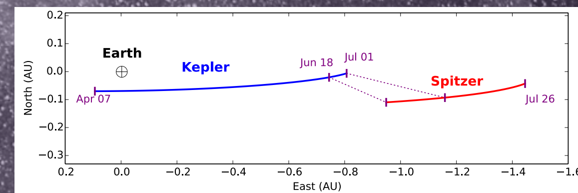
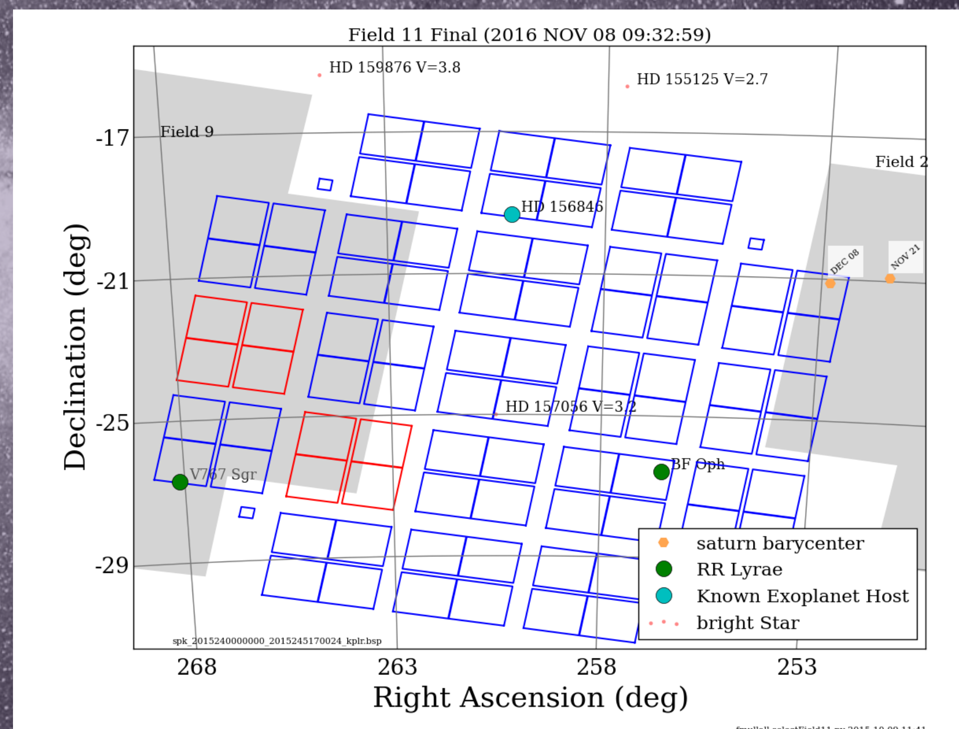
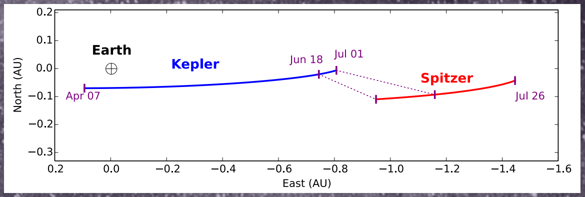


2 *K2C11*

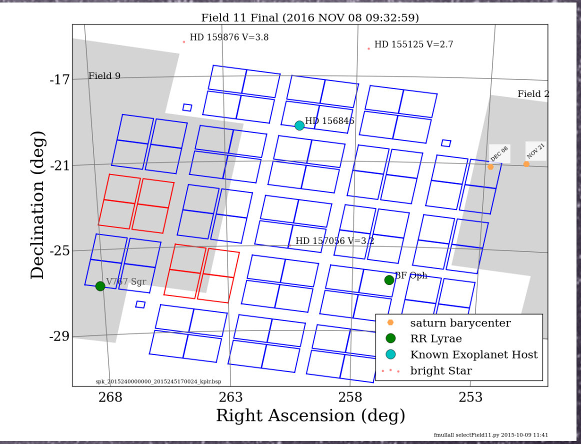


Moving Forward:
K2C9 Synergies

1 *Spitzer*

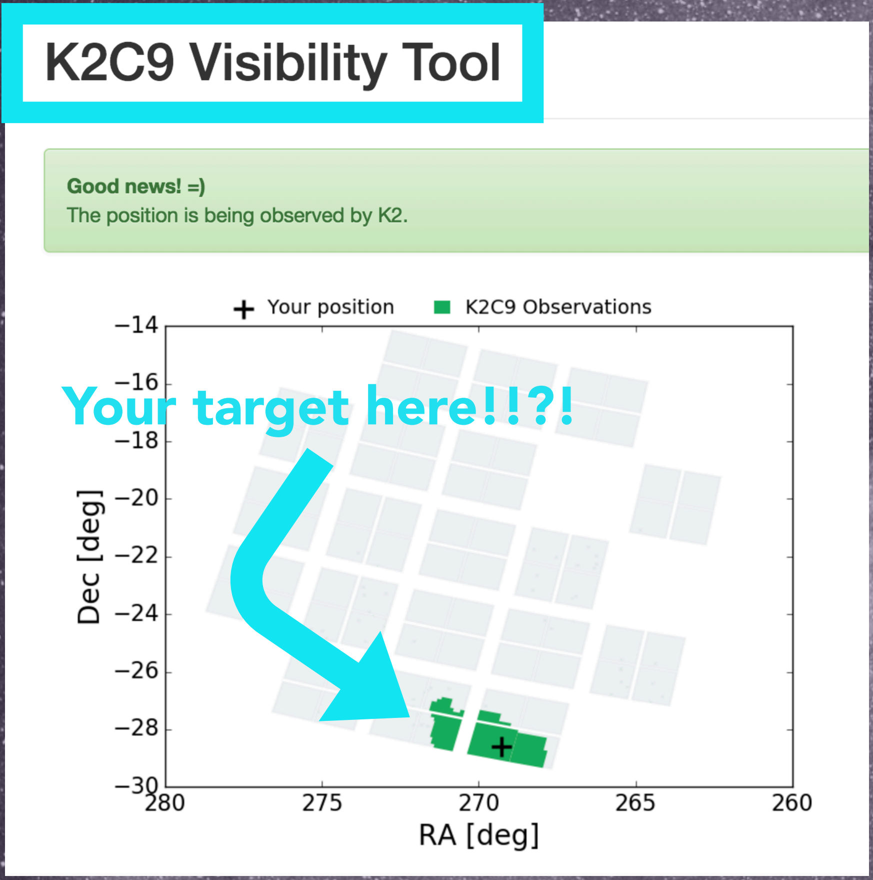


2 *K2C11*



3 Non-microlensing science!

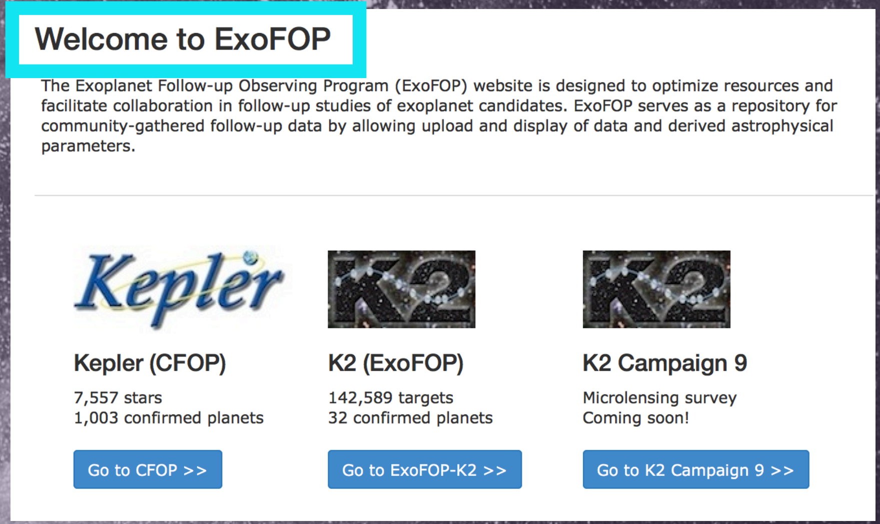
Community Interface

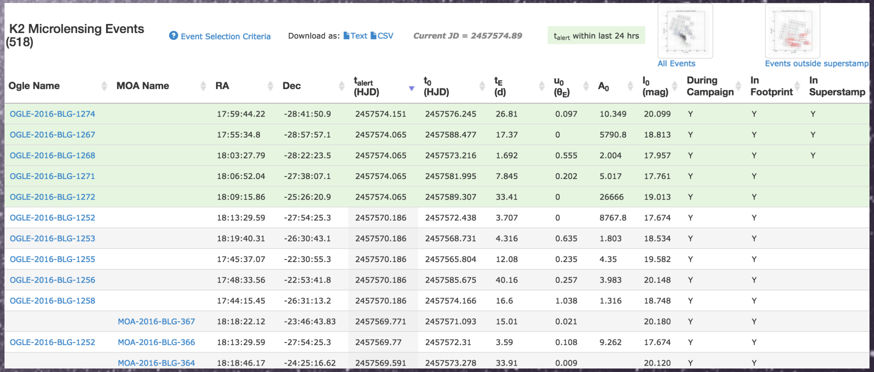


Created by:

G. Barentsen, T. Barclay, R. Poleski

http://k2c9.herokuapp.com/





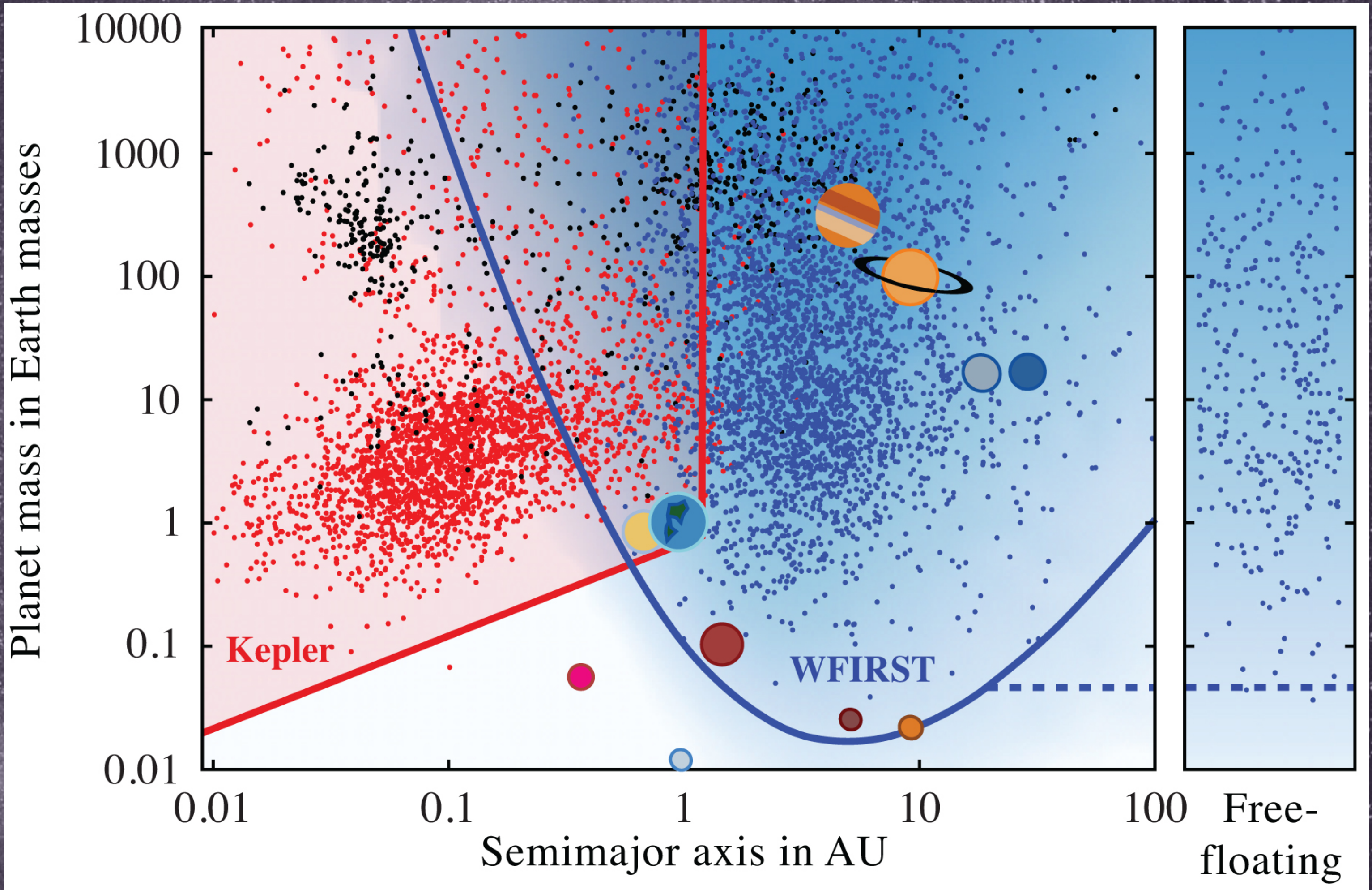
K2 Microlensing Events (518) — Event Selection Criteria — Download as: Text CSV — *Current JD = 2457574.89* — t_{alert} within last 24 hrs — All Events — Events outside superstamp

Ogle Name	MOA Name	RA	Dec	t_{alert} (HJD)	t_0 (HJD)	t_E (d)	u_0 (θ_E)	A_0	I_0 (mag)	During Campaign	In Footprint	In Superstamp
OGLE-2016-BLG-1274		17:59:44.22	-28:41:50.9	2457574.151	2457576.245	26.81	0.097	10.349	20.099	Y	Y	Y
OGLE-2016-BLG-1267		17:55:34.8	-28:57:57.1	2457574.065	2457588.477	17.37	0	5790.8	18.813	Y	Y	Y
OGLE-2016-BLG-1268		18:03:27.79	-28:22:23.5	2457574.065	2457573.216	1.692	0.555	2.004	17.957	Y	Y	Y
OGLE-2016-BLG-1271		18:06:52.04	-27:38:07.1	2457574.065	2457581.995	7.845	0.202	5.017	17.761	Y	Y	
OGLE-2016-BLG-1272		18:09:15.86	-25:26:20.9	2457574.065	2457589.307	33.41	0	26666	19.013	Y	Y	
OGLE-2016-BLG-1252		18:13:29.59	-27:54:25.3	2457570.186	2457572.438	3.707	0	8767.8	17.674	Y	Y	
OGLE-2016-BLG-1253		18:19:40.31	-26:30:43.1	2457570.186	2457568.731	4.316	0.635	1.803	18.534	Y	Y	
OGLE-2016-BLG-1255		17:45:37.07	-22:30:55.3	2457570.186	2457565.804	12.08	0.235	4.35	19.582	Y	Y	
OGLE-2016-BLG-1256		17:48:33.56	-22:53:41.8	2457570.186	2457585.675	40.16	0.257	3.983	20.148	Y	Y	
OGLE-2016-BLG-1258		17:44:15.45	-26:31:13.2	2457570.186	2457574.166	16.6	1.038	1.316	18.748	Y	Y	
	MOA-2016-BLG-367	18:18:22.12	-23:46:43.83	2457569.771	2457571.093	15.01	0.021		20.180	Y	Y	
OGLE-2016-BLG-1252	MOA-2016-BLG-366	18:13:29.59	-27:54:25.3	2457569.77	2457572.31	3.59	0.108	9.262	17.674	Y	Y	
	MOA-2016-BLG-364	18:18:46.17	-24:25:16.62	2457569.591	2457573.278	33.91	0.009		20.120	Y	Y	

Created and curated by:

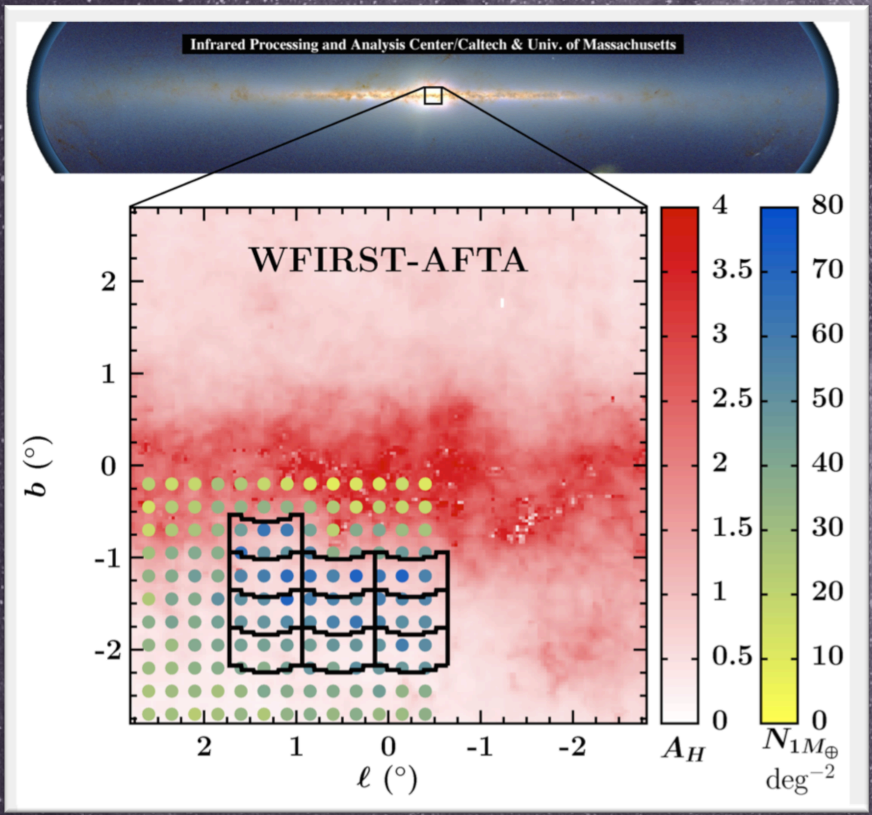
R. Akeson, R. Street

Microlens Parallax Satellite III. *WFIRST*



Spergel+ (2015) arXiv:1503.03757

Microlens Parallax Satellite III. *WFIRST*

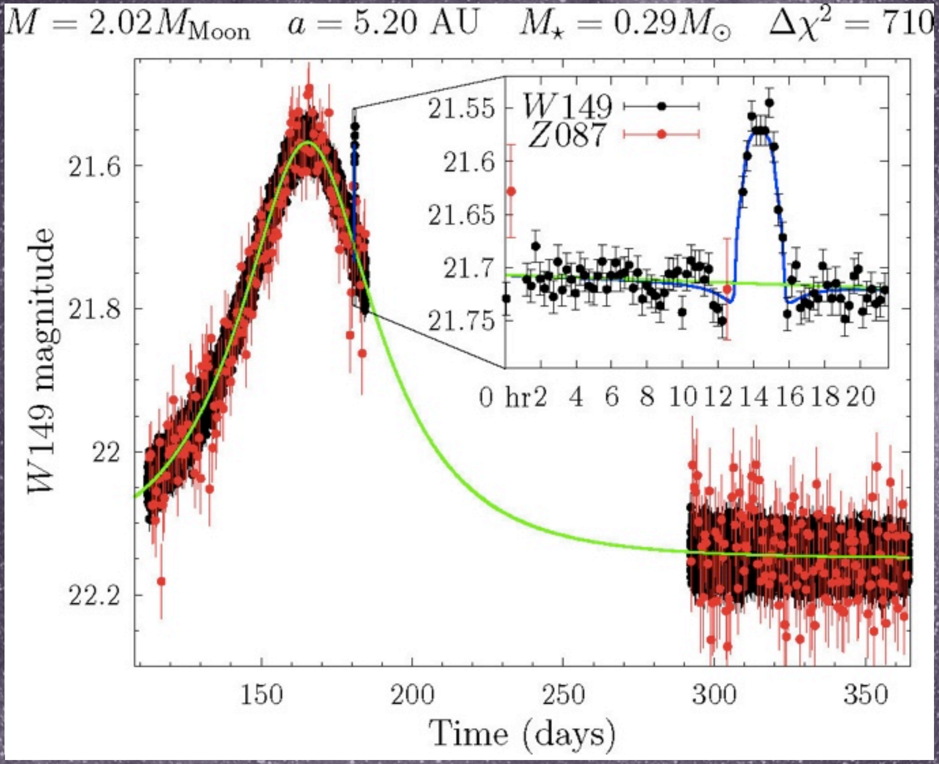


Spergel+ (2015) arXiv:1503.03757

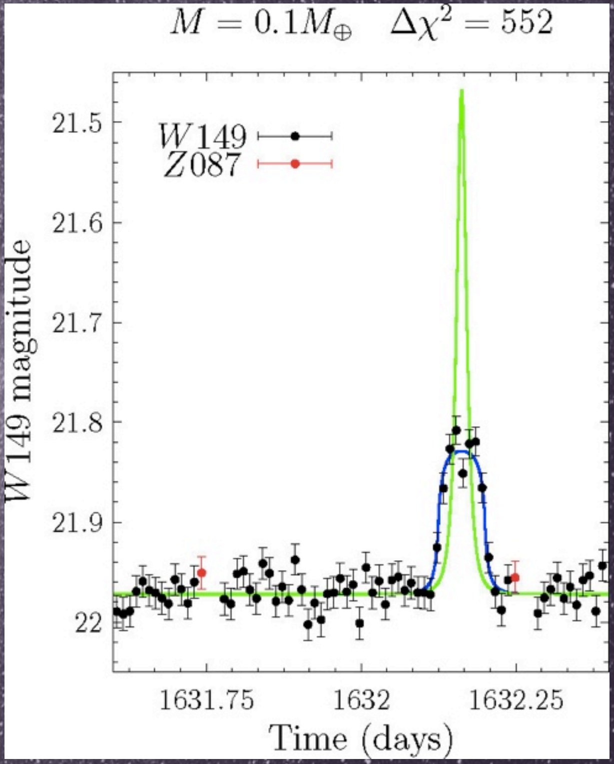
Launch	2024/2025
Orbit	L2
Survey Duration	432 d
	(6 72 d seasons)
Survey Area	0.281 deg^2
Number of fields	10
Bound Exoplanets	~3000
Free-floating	~300

Microlens Parallax Satellite III. *WFIRST*

Bound Exoplanet



Free-floating

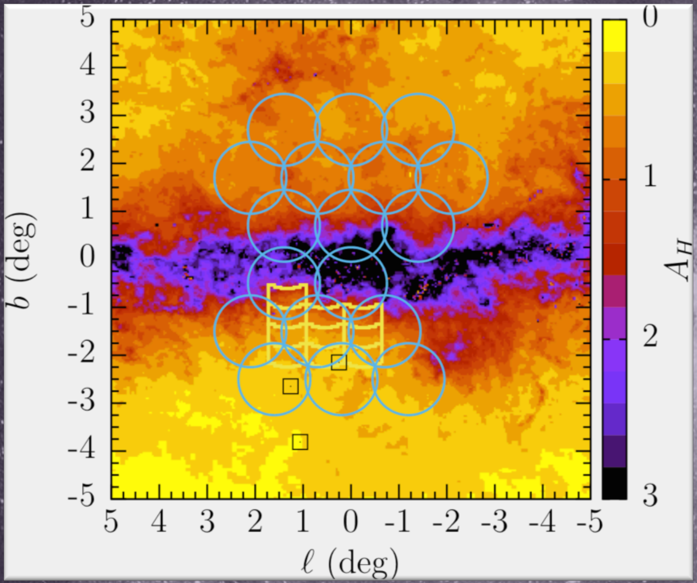


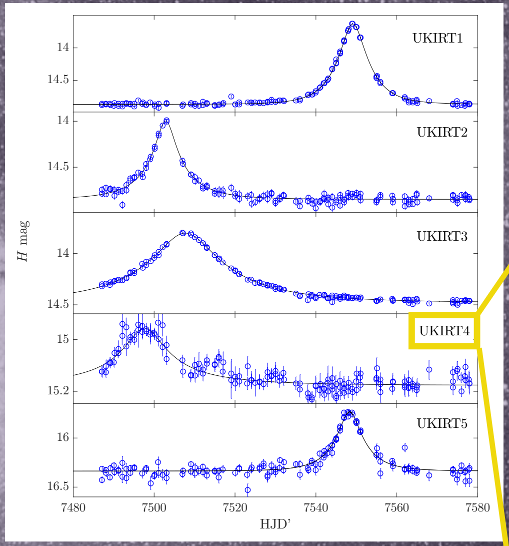
Spergel+ (2015) arXiv:1503.03757

Jet Propulsion Laboratory
California Institute of Technology

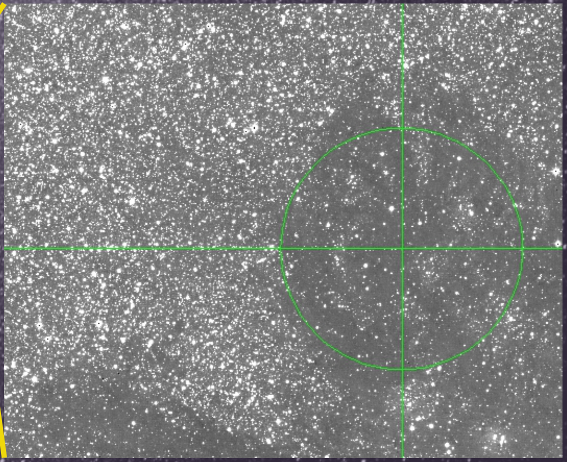
Microlens Parallax Satellite III. *WFIRST* Preparatory Work

3D Optical-to-NIR Extinction Map





NIR Event Rate



Come Learn and Discuss Microlensing!

Topics Include:

***K2*C9!**

Spitzer!

WFIRST!

Don't worry: Conference preceded by (free!) half-day microlensing tutorial!

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http://nexsci.caltech.edu/conferences/2017/microlensing