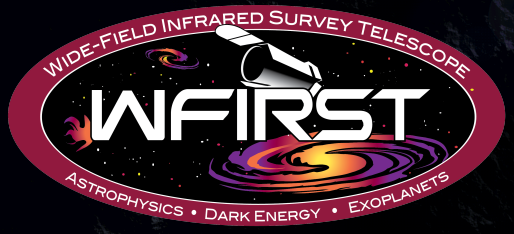
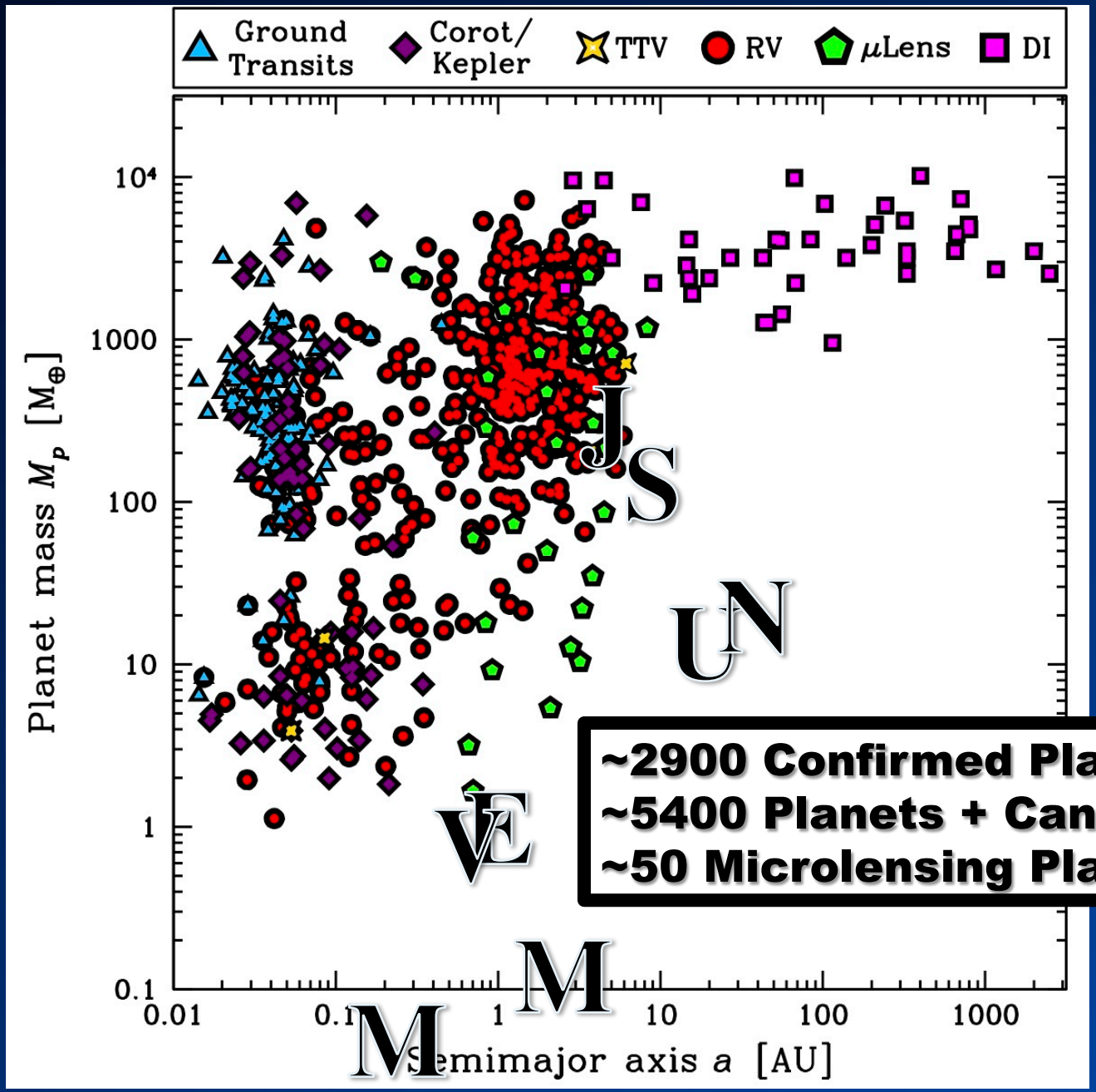
WFIRST, K2, and Microlensing.

2016 Sagan Summer Workshop
July 22, 2016



Scott Gaudi
The Ohio State University
Jet Propulsion Laboratory

(Collaborators: μFUN, Andy Gould, Jennifer Yee, Christian Clanton, Calen Henderson, Matthew Penny, WFIRST SDTs and μSIT)


Ground Transits
Corot/ Kepler
TTV
RV
μLens
DI
Planet mass M_p [$M_\oplus$]
Semimajor axis a [AU]
0.1
1
10
100
1000
10^4
0.01
0.1
1
10
100
1000
J
S
U
N
V
E
M
M
~2900 Confirmed Planets
~5400 Planets + Candidates
~50 Microlensing Planets :-(

The Watershed.

watershed n.

1. An area or ridge of land that separates waters flowing to different rivers, basins, or seas.

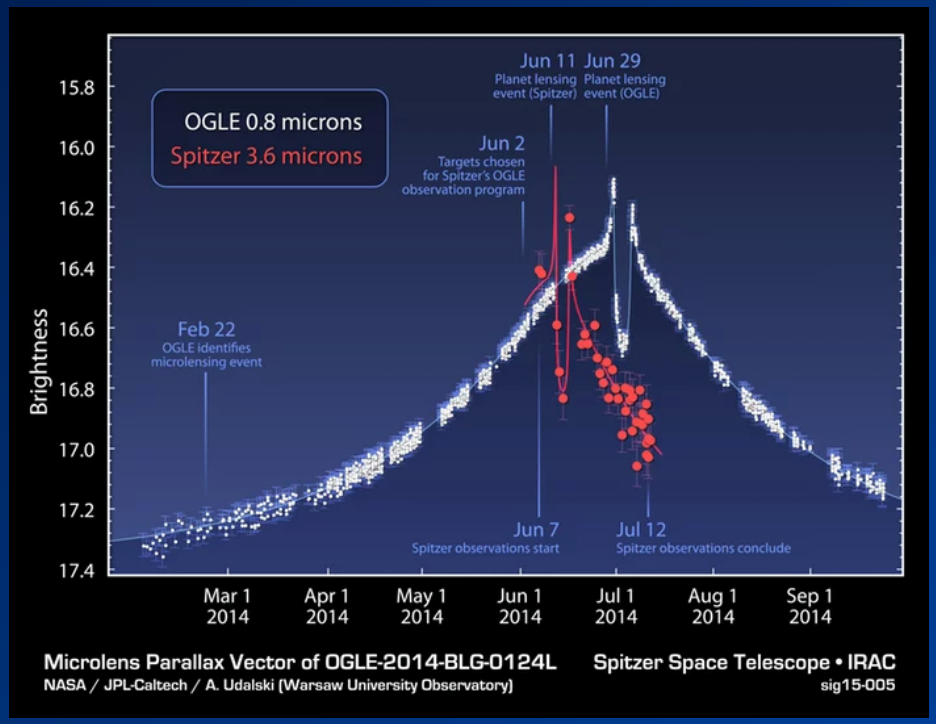
2. An event or period marking a turning point in a course of action or state of affairs.

The Watershed:

The 2010 Decadal Survey.

The Microlensing Watershed.

- **Spitzer & K2C9+K2C11.**
  - **Masses and distances.**
  - **Mass function and Galactic distribution of planets.**
  - **Free-floating planets masses (K2C9).**
- KMTNet
  - 3 1.6m telescopes, 4 sq. degree FOV
  - ~50 detections/year.
- Euclid & WFIRST
  - Detections *en masse*.
  - Complete the census of exoplanets started by *Kepler*.

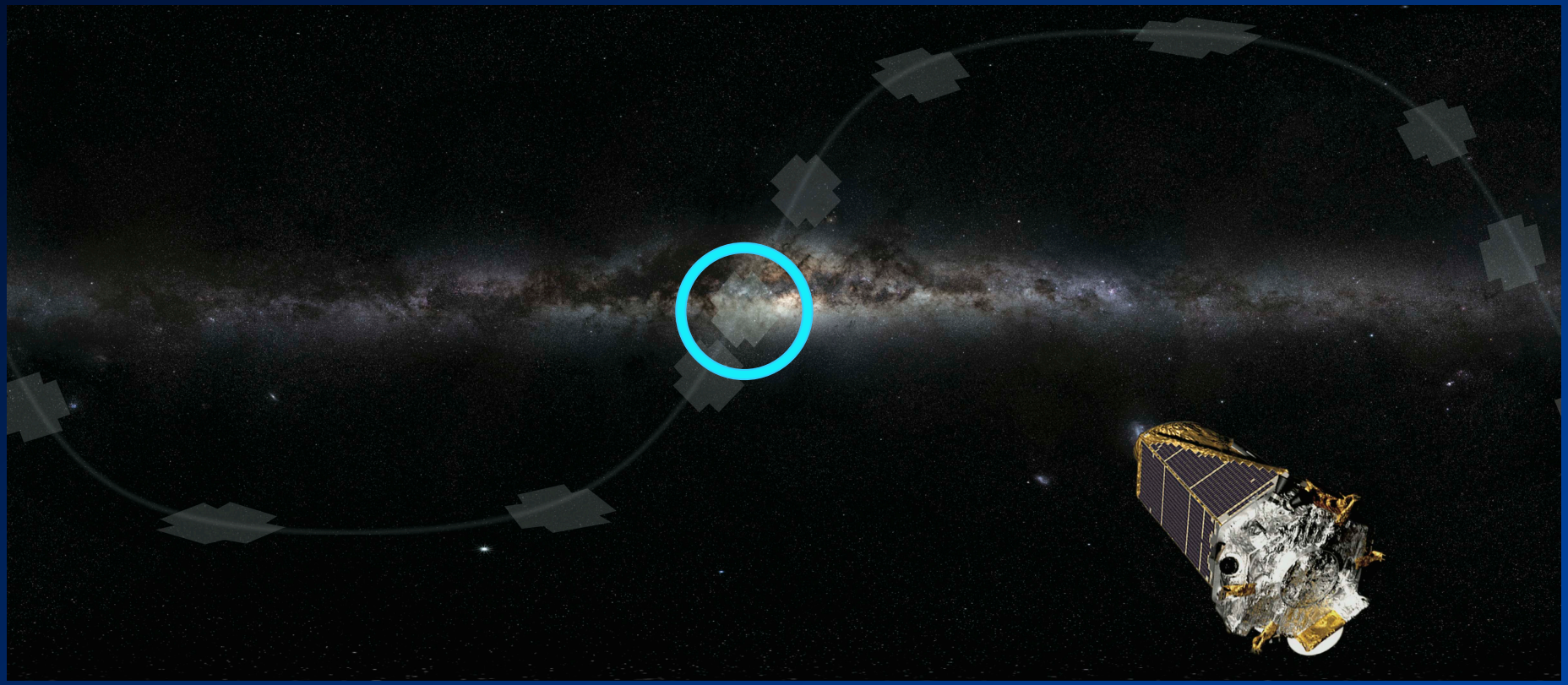


(Udalski et al. 2014; Yee et al. 2014, 2015; Calchi Novati et al. 2014, 2015; Zhu et al. 2015a,b,c; Shvartzvald et al. 2015; Street et al. 2015; Poleski et al. 2015; Henderson et al. 2015; Bozza et al. 2016)

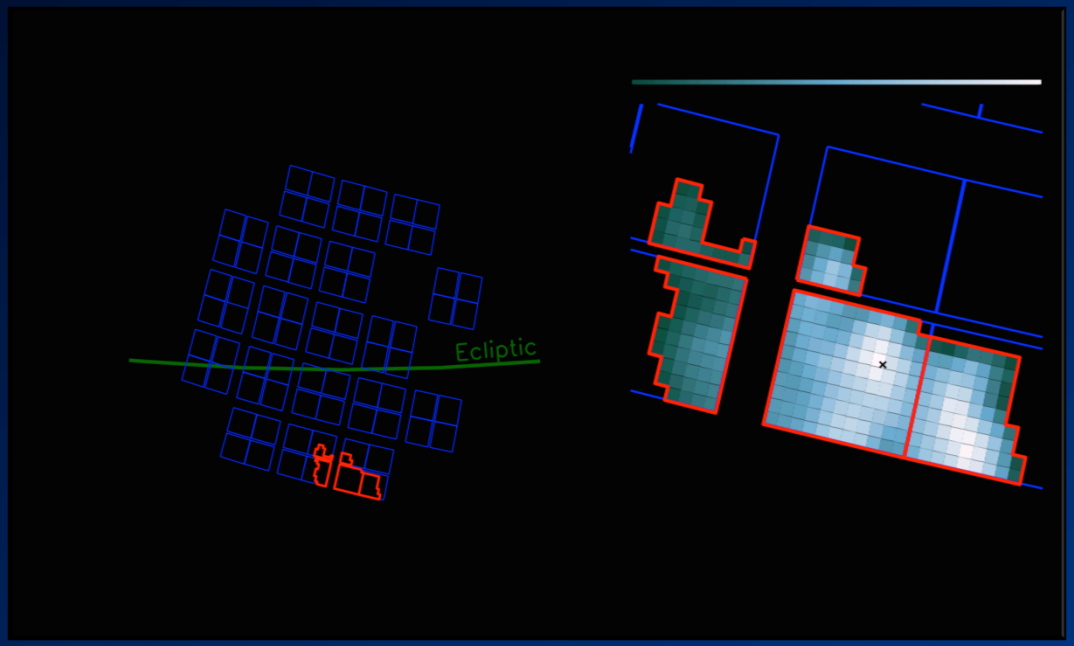
K2C9 Planet Masses.

K2's Campaign 9 (*K2*C9):

A Joint Ground+Space Microlensing Survey



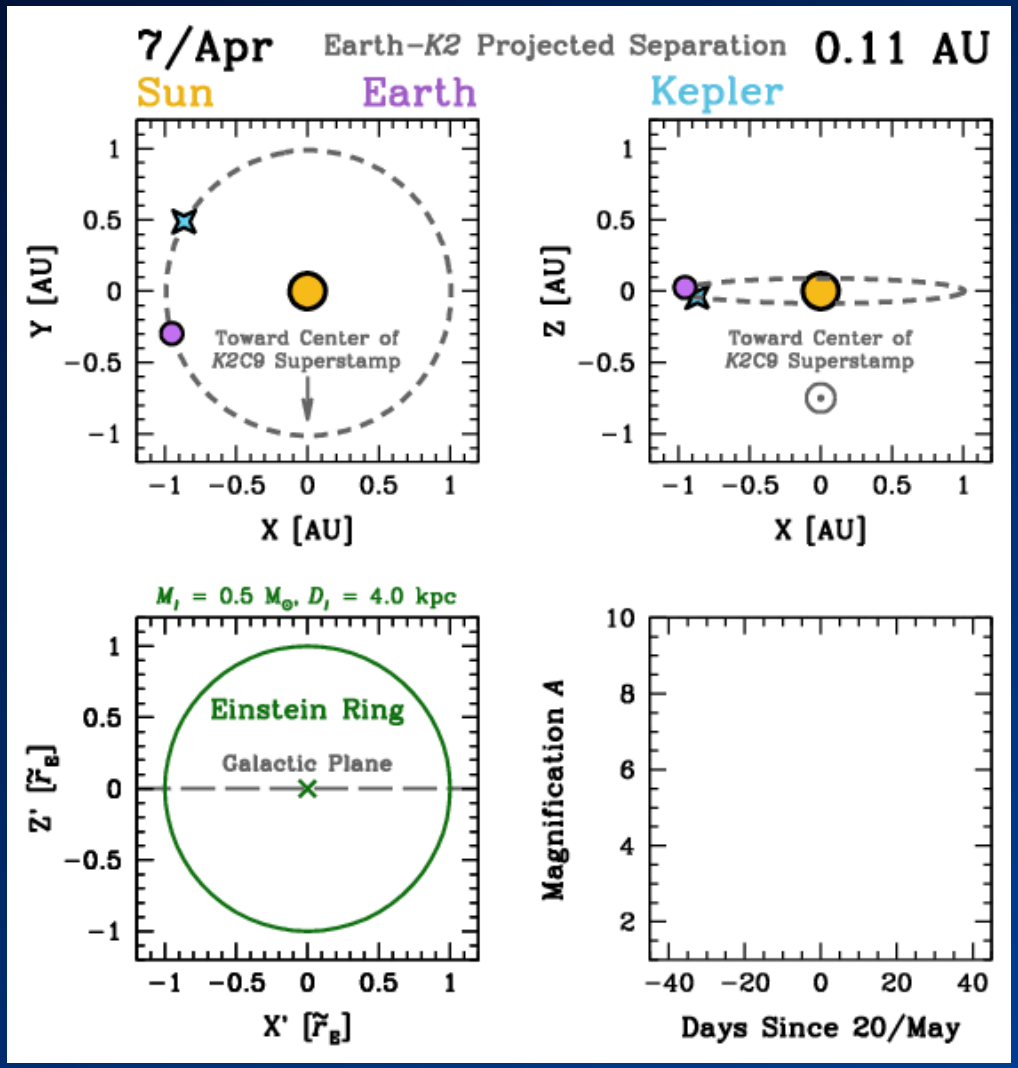
What is *K2C9*?



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+ (2015) arXiv:1512.09142
Uses methodology of Poleski (2016) MNRAS, 455, 3656

Satellite Parallax.



Henderson+ (2015) arXiv:1512.09142

Science Goals: Quality versus Quantity

Addressing (relatively) Unexplored Demographic Questions

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

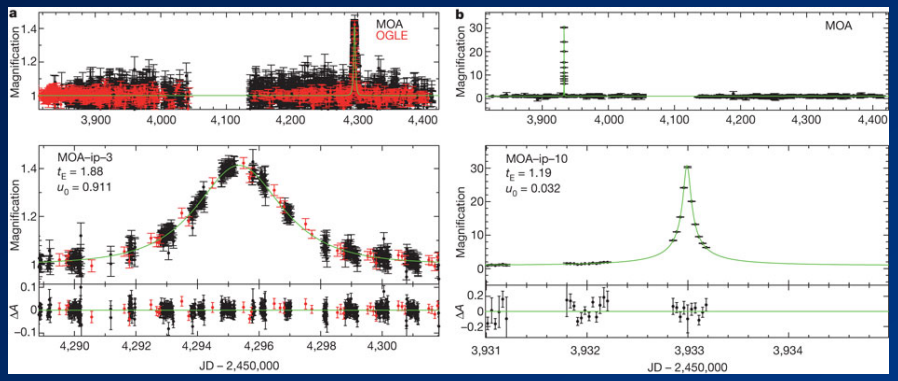
Science Goals: Quality versus Quantity

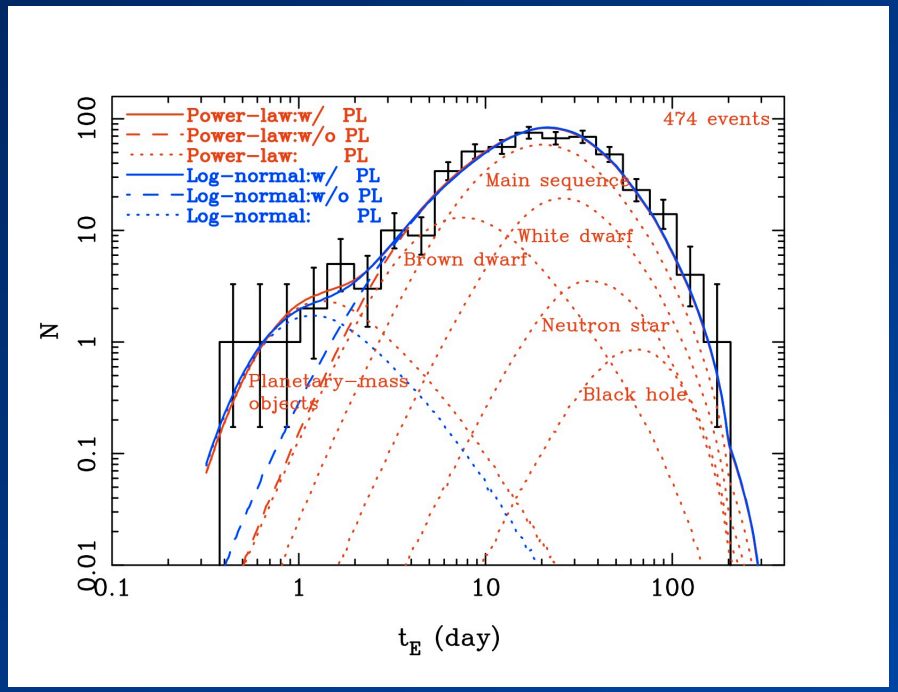
Addressing (relatively) Unexplored Demographic Questions

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

Free Floating Planets.

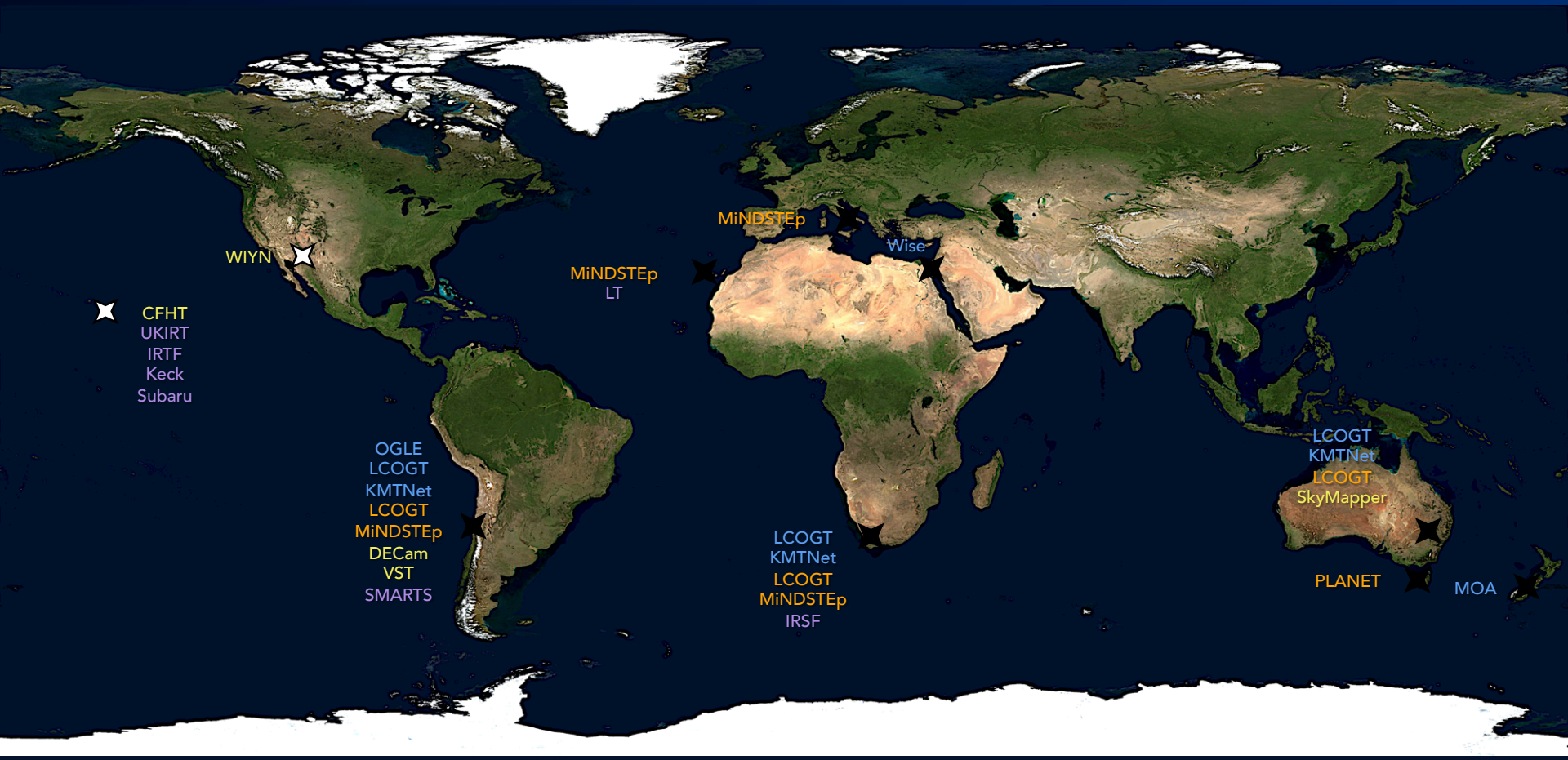
- Excess of short time scale events relative to expected stellar/brown dwarf contribution.
- Unbound or wide-separation planets.
- Implies roughly 2 Jupiter-mass free-floating planets per star.





(Sumi et al. 2011; MOA + OGLE Collaborations)

Simultaneous Ground-based Resources

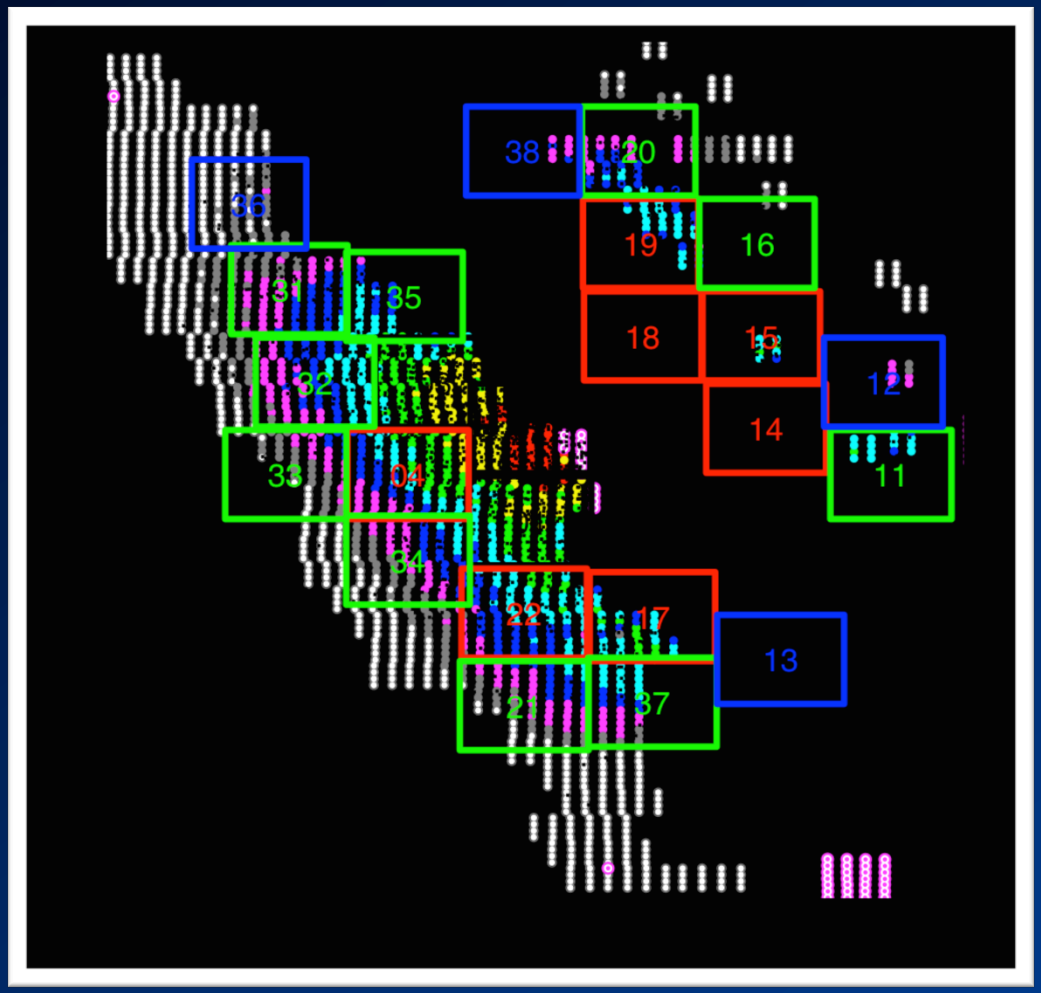


Automated Survey
Multiband Monitoring

High-cadence Follow-up
Near-infrared Source Fluxes

Henderson+ (2015) arXiv:1512.09142

KMTNet

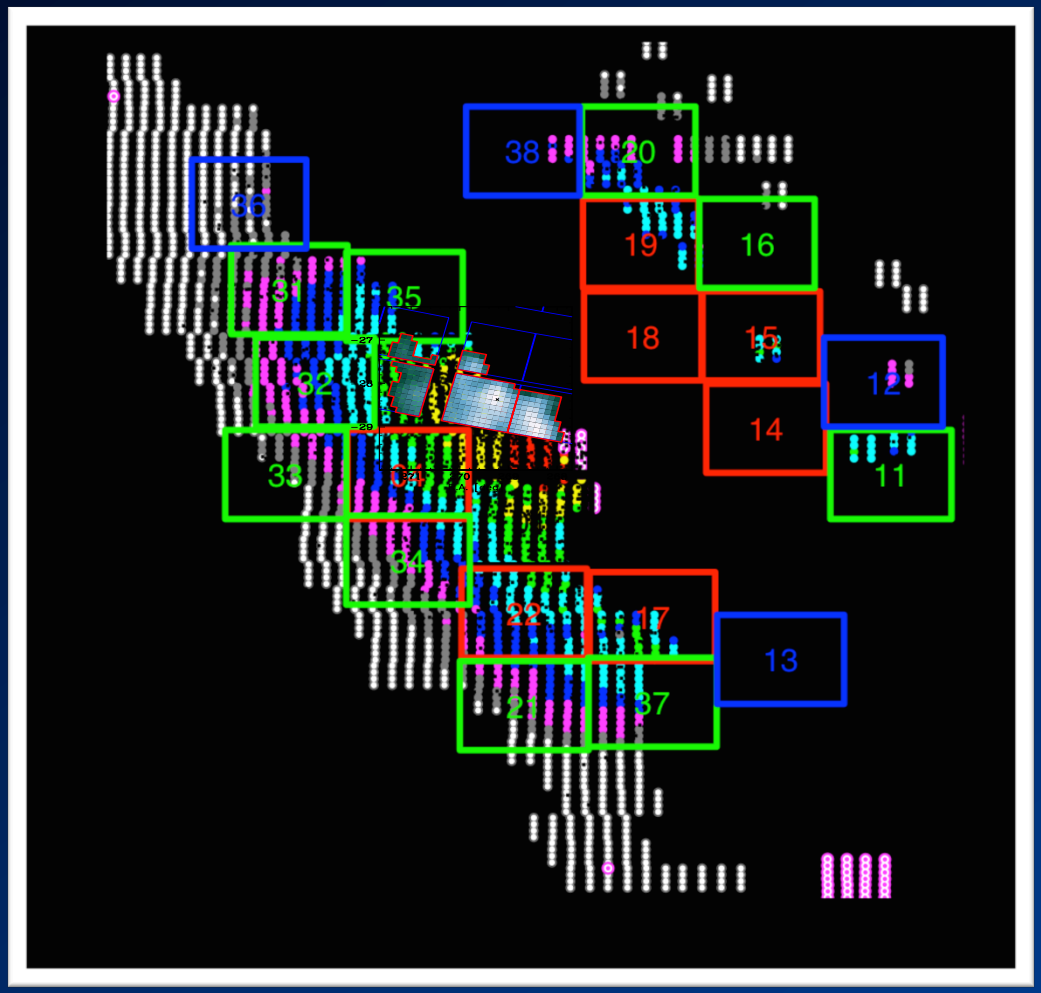


15m	Earth
1h	Nep
2.5h	Sat
5h	Jup

Declination

Right Ascension

KMTNet



Declination

Right Ascension

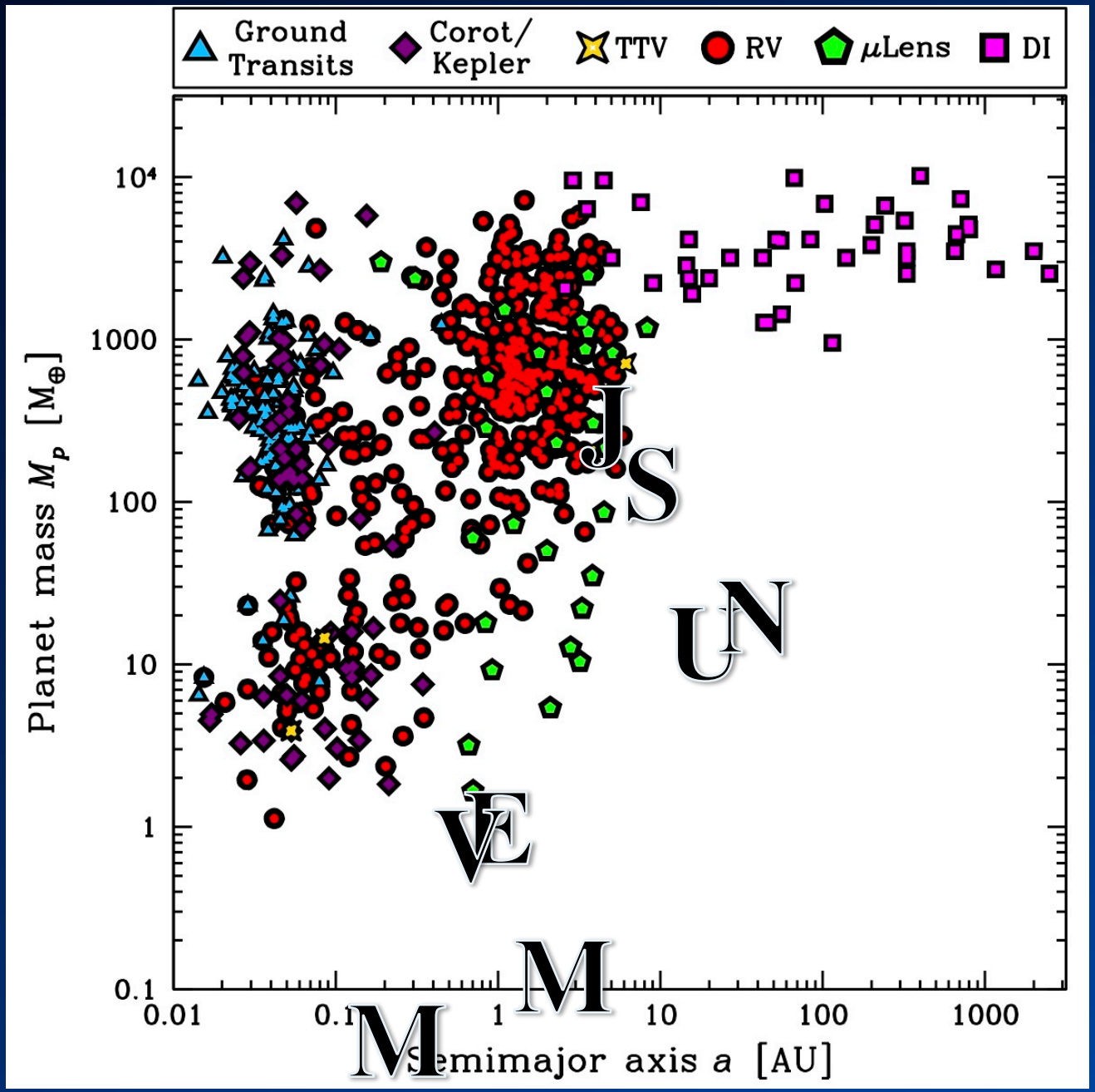
15m	Earth
1h	Nep
2.5h	Sat
5h	Jup

Preliminary *K2C9* Parallax Inventory

Total events	110 (180)
Bound Planets	4
FFP Candidates	7 (13)
Stellar Binaries	8
Long-timescale	13

Values are, generally, lower limits!!

Toward a Complete Galactic (Statistical) Census of Exoplanets.


Ground Transits
Corot/ Kepler
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Planet mass M_p [$M_\oplus$]
10^4
1000
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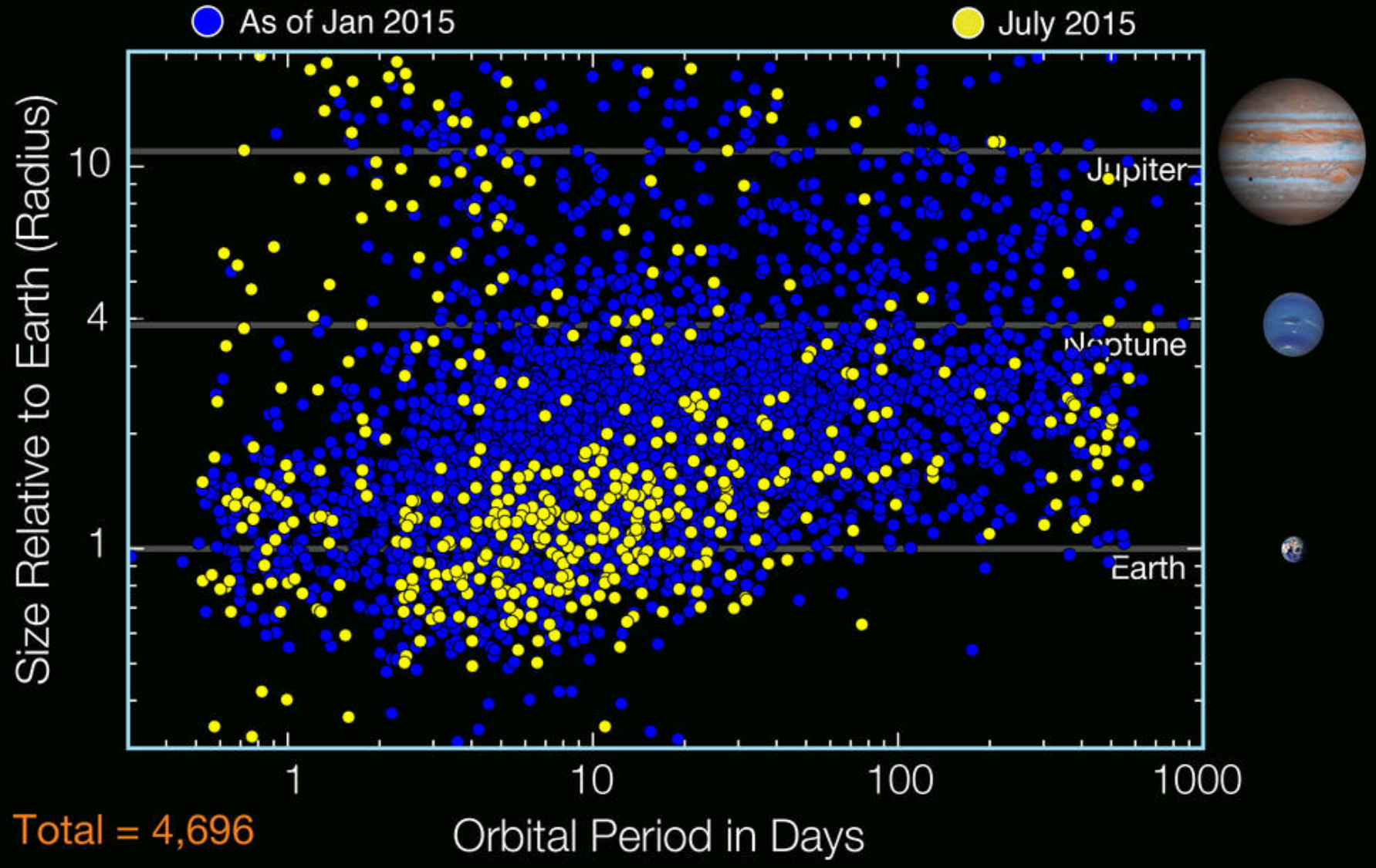
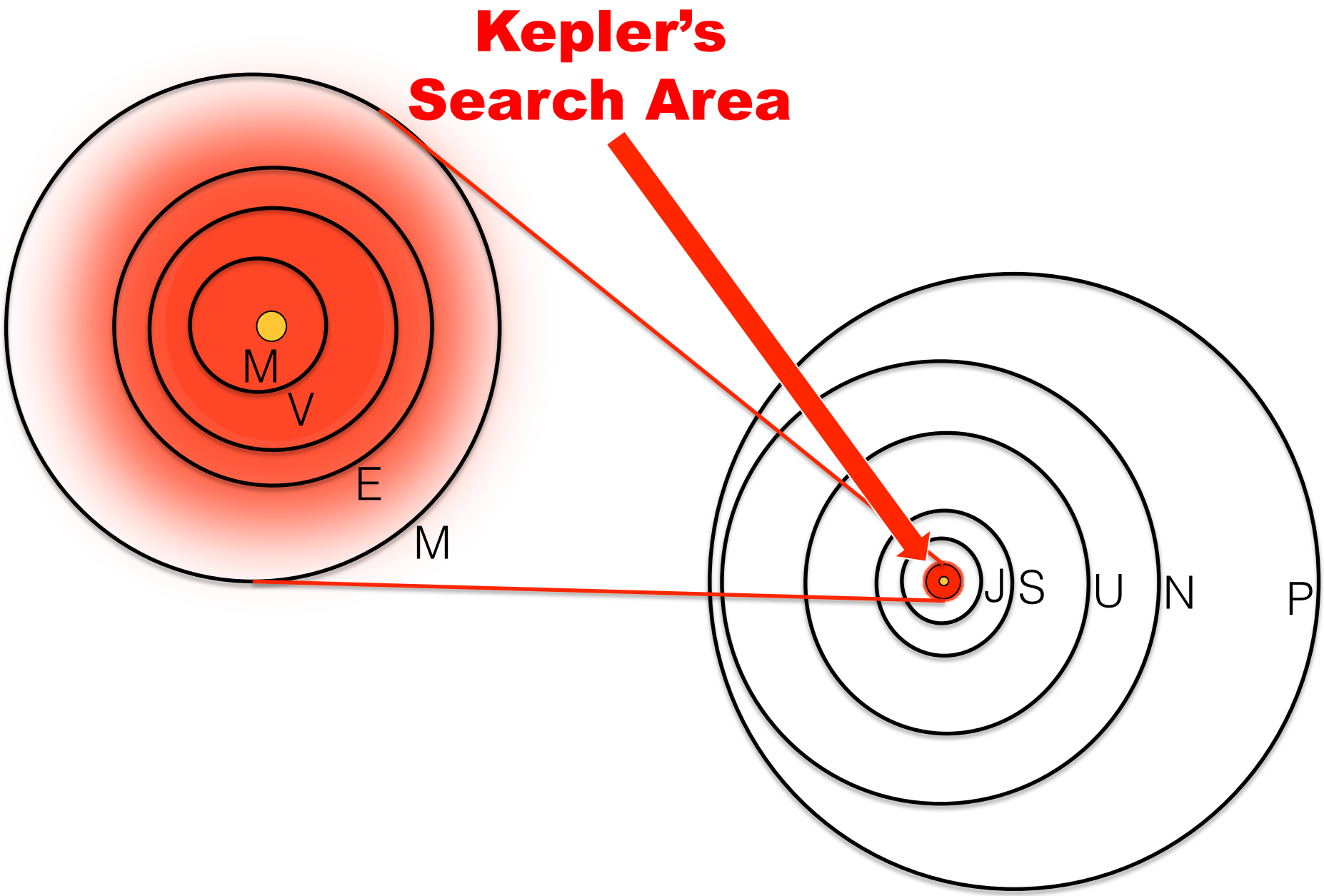
10
1
0.1
0.01
0.1
1
10
100
1000
Semimajor axis a [AU]
J
S
U
N
V
E
M
M

New Kepler Planet Candidates

As of July 23, 2015




Kepler's
Search Area
M
V
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M
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S
U
N
P

Why complete the census?

- A complete census is likely needed to understand planet formation and evolution.
  - Most giant planets likely formed beyond the snow line.
  - Place our solar system in context.
  - Water for habitable planets likely delivered from beyond the snow line.
  - Understand the frequency of planet formation in different environments.

Why complete the cen

- A complete census is likely n
  understand planet forma ion.
  - Most giant planets li nd the snow line.
  - Place ou ontext.
  - Wa lanets likely delivered from line.
  - the frequency of planet formation in nt environments.

Blah, blah, blah.

So really, why complete the census?

1995: A Planetary Companion to 51 Peg

(Mayor & Queloz 1995)

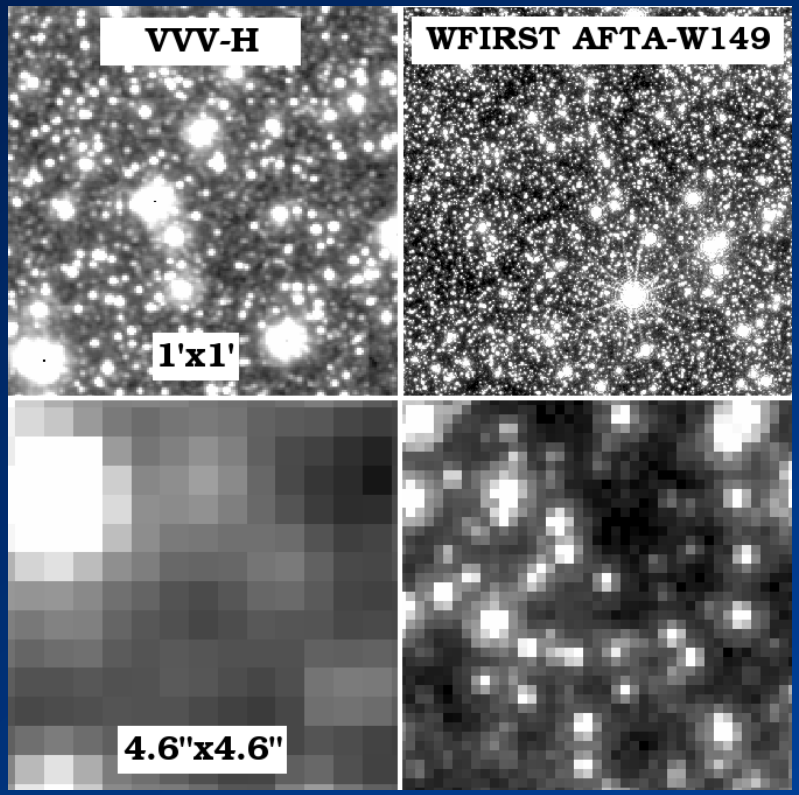
Mother Nature is More Imaginative Than We Are.

Earth Mass and Below?

- Monitor hundreds of millions of bulge stars continuously on a time scale of ~10 minutes.
  - Event rate ~10^{-5}/year/star.
  - Detection probability ~0.1-1%.
  - Shortest features are ~30 minutes.
- Relative photometry of a few %.
  - Deviations are few – 10%.
- Resolve main sequence source stars for smallest planets.
- Masses: resolve background stars for primary mass determinations.

Ground vs. Space.

- Infrared.
  - More extincted fields.
  - Smaller sources.
- Resolution.
  - Low-magnification events.
  - Isolate light from the lens star.
- Visibility.
  - Complete coverage.
- Smaller systematics.
  - Better characterization.
  - Robust quantification of sensitivities.



Science enabled from space: sub-Earth mass planets, habitable zone planets, free-floating Earth-mass planets, mass measurements.

(Bennett & Rhie 2002)

WFIRST.

What is the Wide Field InfraRed Survey Telescope?

- #1 recommendation of the 2010 Decadal Survey for a large space mission.
- Notional mission, based on several different inputs, including:
  - JDEM-Omega (Gehrels et al.)
  - MPF (Bennett et al.)
  - NISS (Stern et al.)
- Three equal science areas:
  - Dark energy (SNe, Weak Lensing, BAO).
  - Exoplanet microlensing survey.
  - GO program including a Galactic plane survey.

WFIRST Designs.

- NASA put together two science definition teams to come up with “Design Reference Missions”
- Original Science Definition Team (Green et al. arXiv:1208.4012, arXiv: 1108.1374)
  - DRM1 (1.3m)
  - DRM2 (1.1m)
- AFTA/WFIRST Science Definition Team (Dressler et al. arXiv: 1210.7809, Spergel et al. arXiv:1305.5425, arXiv:1503.03757)
  - Studied the application of one of the National Reconnaissance Office (NRO) telescopes to WFIRST
    - Two 2.4m space-qualified telescopes, donated to NASA
    - Mirrors and spacecraft assemblies.
  - Also considered a coronagraph and serviceability.

Is WFIRST Real?

- Yes!
- FY16 appropriation provides $90M for WFIRST (+$76M more than OMB request) and directs NASA to start formulation.
- New start (KDP-A) February 18, 2016.
- WFIRST Science Investigation Team Proposals were due on October 15, 2015, selected proposals announced on December 18, 2015.

WFIRST-AFTA.

	WFIRST-AFTA
Eff. Aperture	2.28m
FOV	0.281 deg^2
Wavelengths	0.7-2 μm
FWHM@1μm	0.10”
Pixel Size	0.11”
Lifetime	5+1 years
Orbit	L2

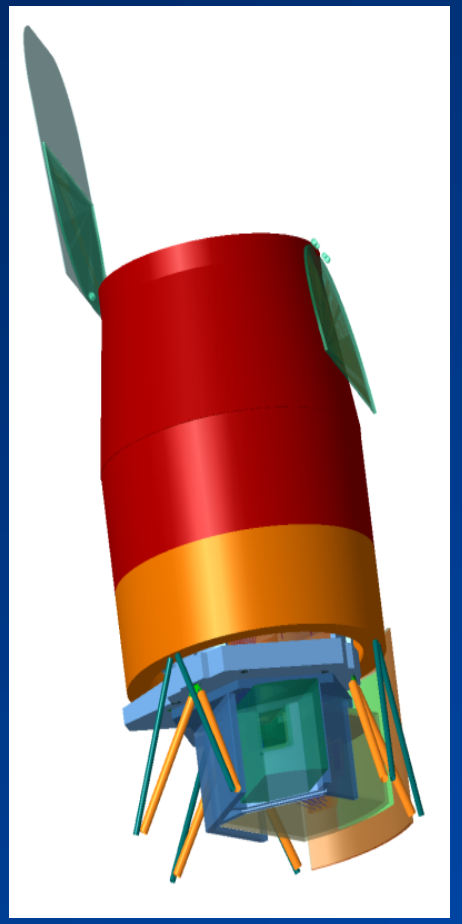
Wide-Field Instrument

- Imaging & spectroscopy over 1000's sq deg.
- Monitoring of SN and microlensing fields
- 0.7 – 2.0 micron bandpass
- 0.28 sq deg FoV (100X JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 4 filter imaging, grism + IFU spectroscopy

Coronagraph

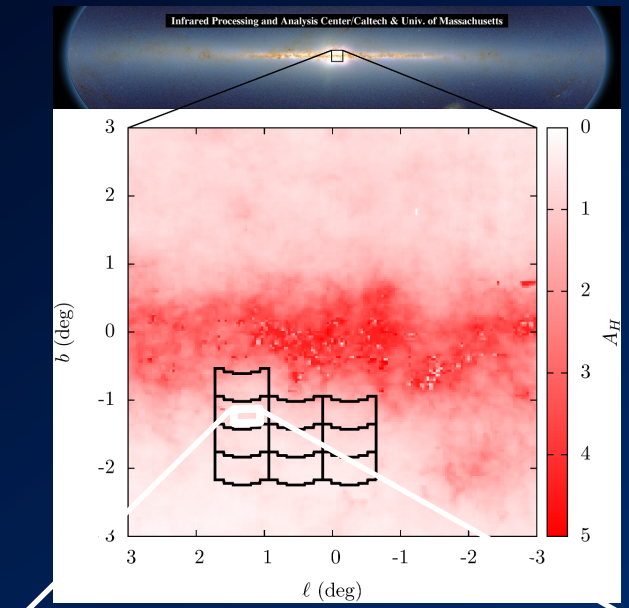
Imaging of ice & gas giant exoplanets

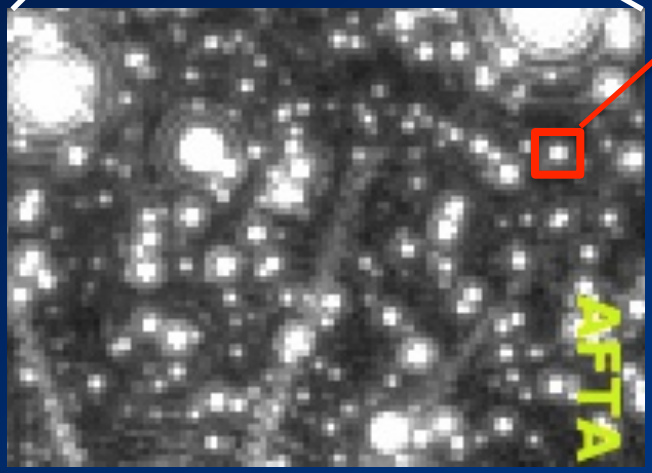
- Imaging of debris disks
- 400 – 1000 nm bandpass
- 10^{-9} contrast
- 200 milli-arcsec inner working angle

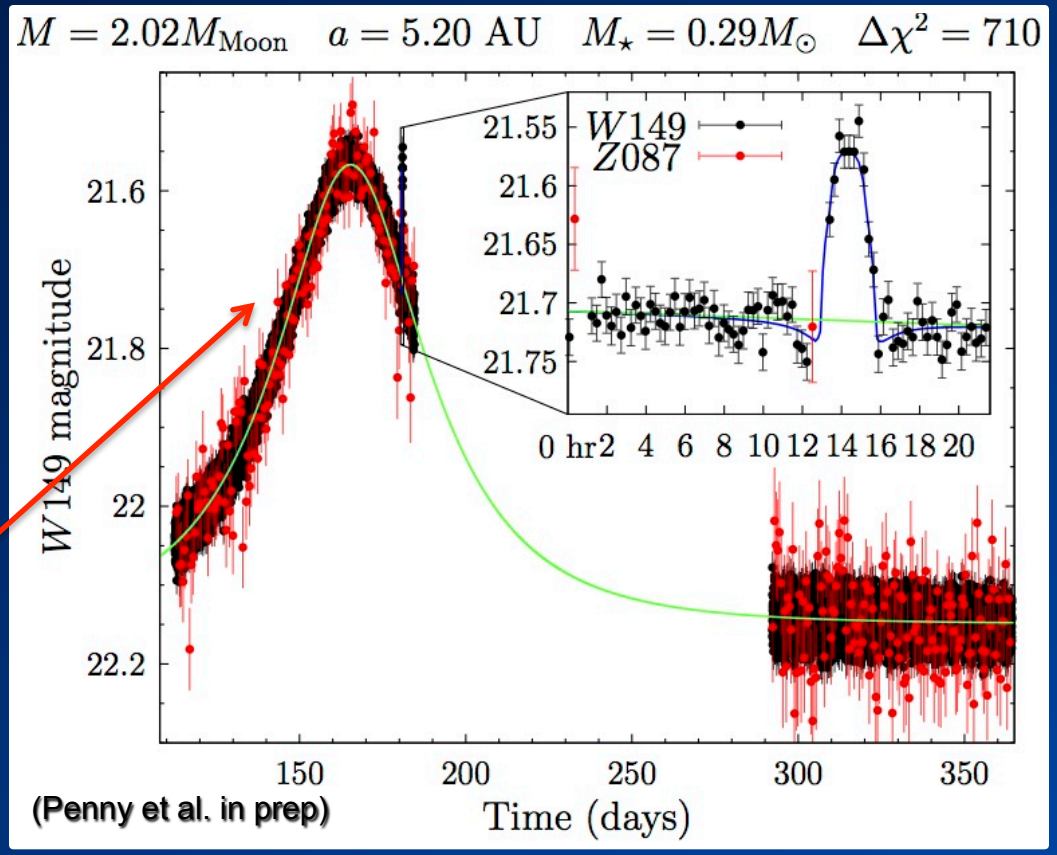


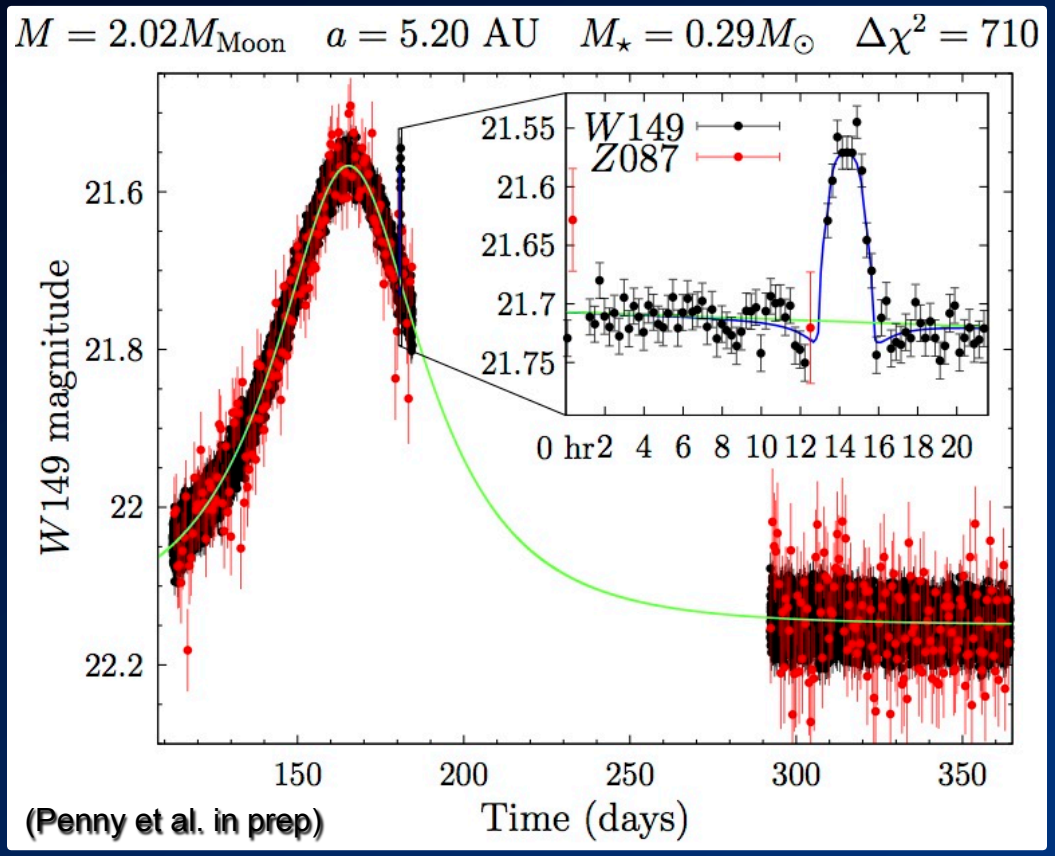
Microlensing Simulations.

(Matthew Penny)

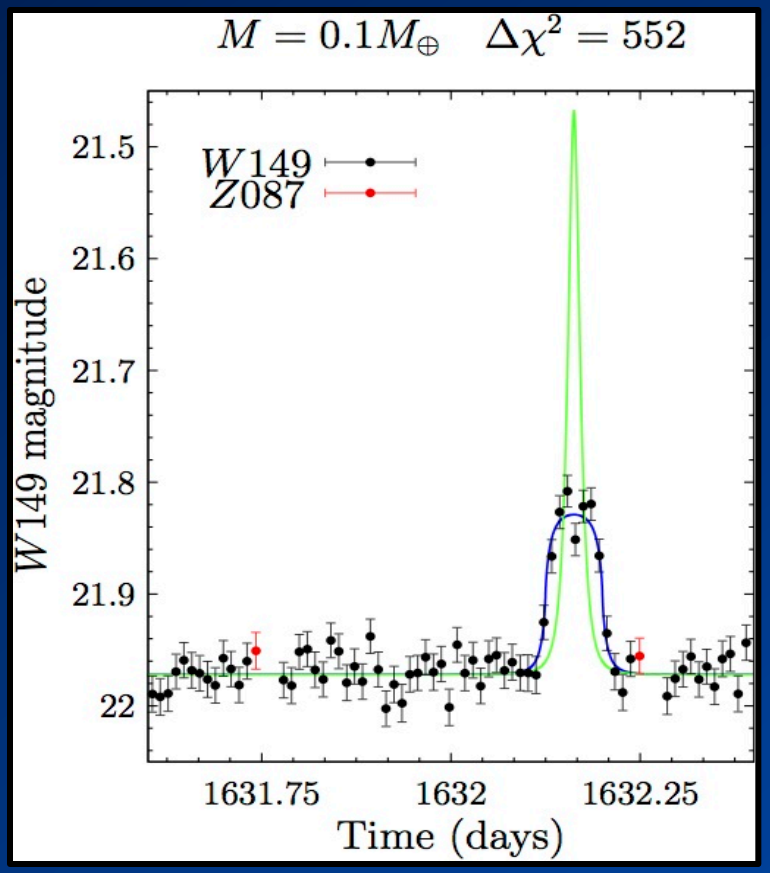




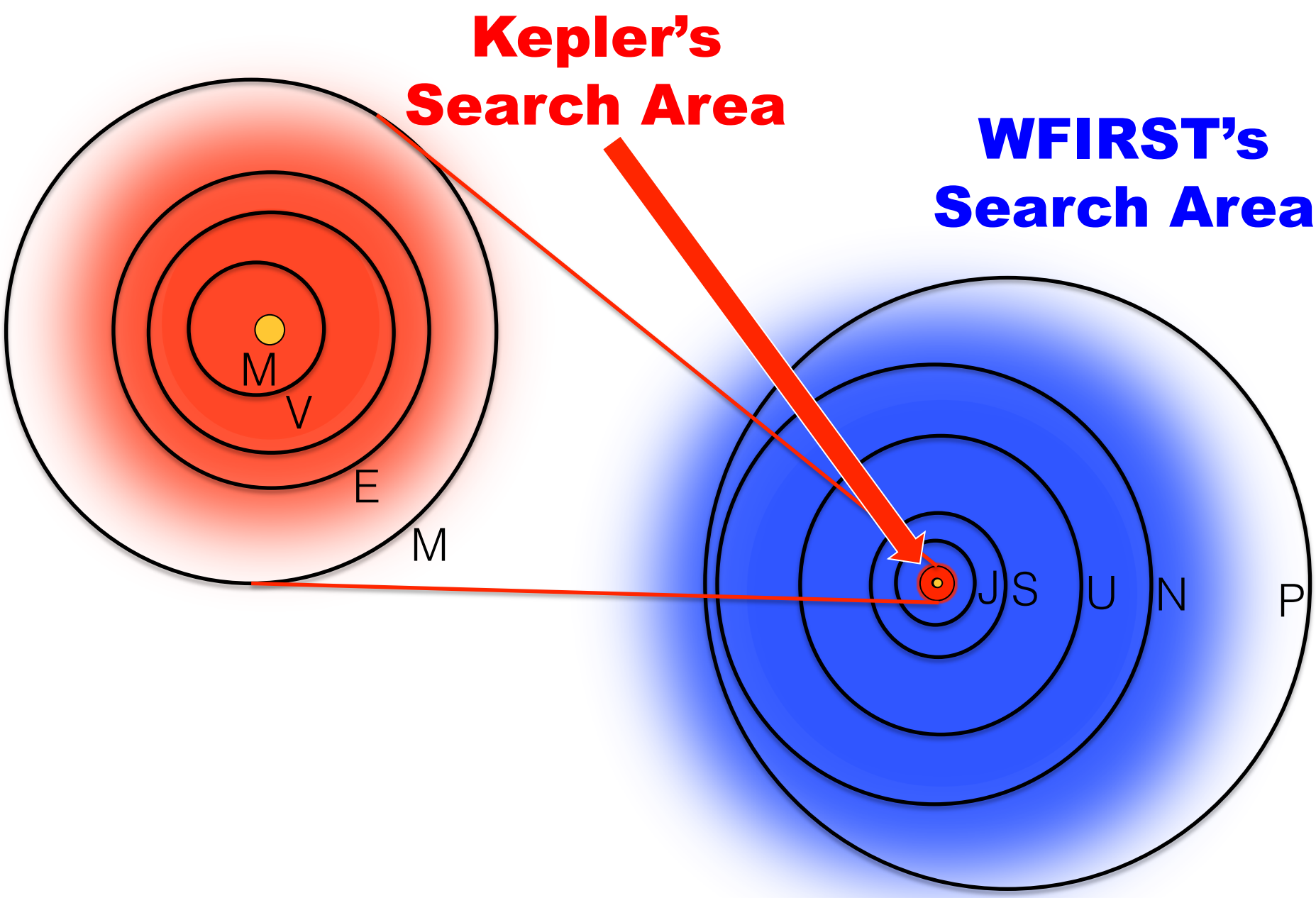




2 × Mass of the Moon @ 5.2 AU (~27 sigma)



Free floating Mars (~23 sigma)


Kepler's
Search Area
WFIRST's
Search Area
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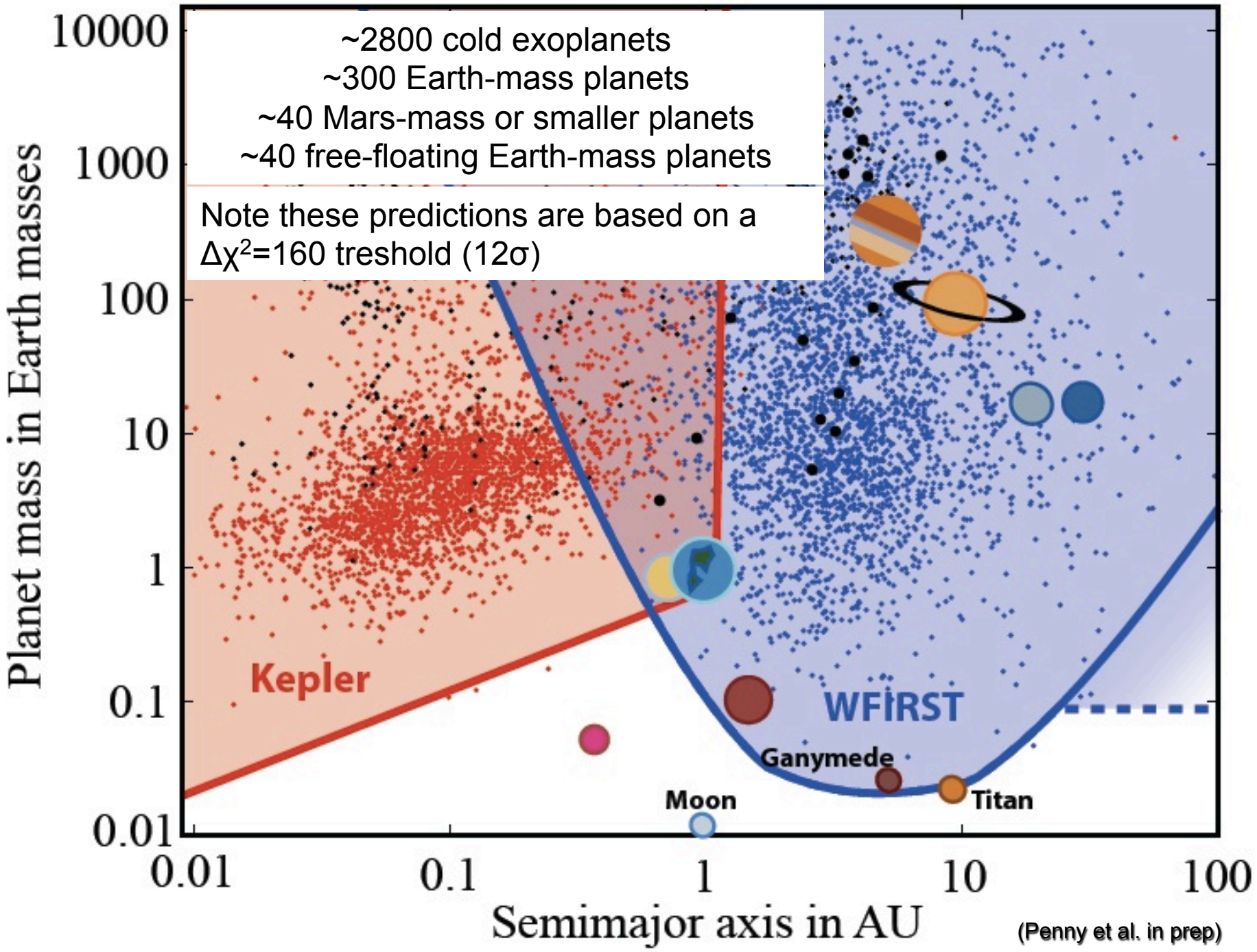
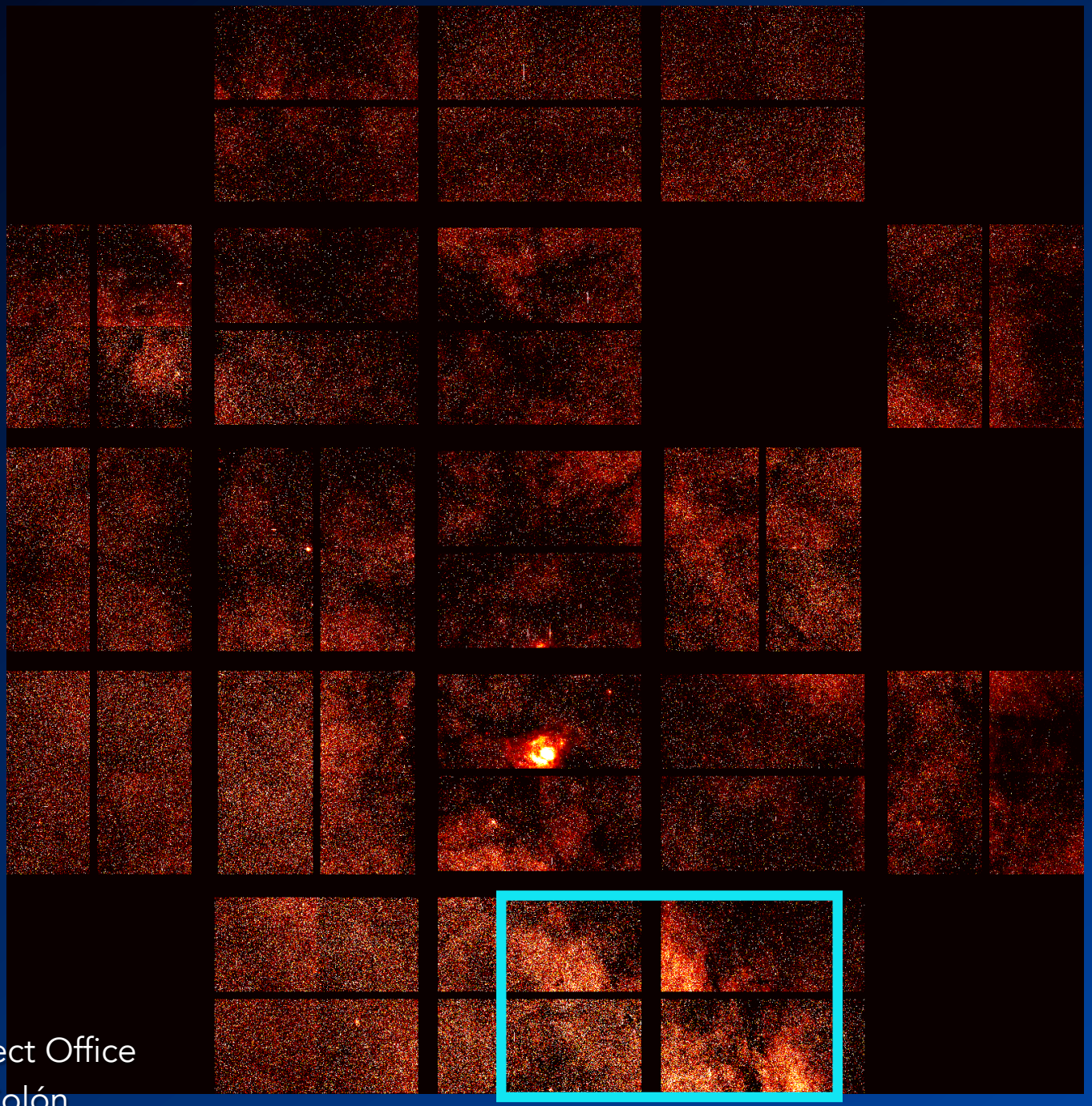

~2800 cold exoplanets
~300 Earth-mass planets
~40 Mars-mass or smaller planets
~40 free-floating Earth-mass planets
Note these predictions are based on a
Δχ²=160 treshold (12σ)
Kepler
WFIRST
Ganymede
Titan
Moon
Planet mass in Earth masses
Semimajor axis in AU
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
(Penny et al. in prep)

Is there a planet in my data?

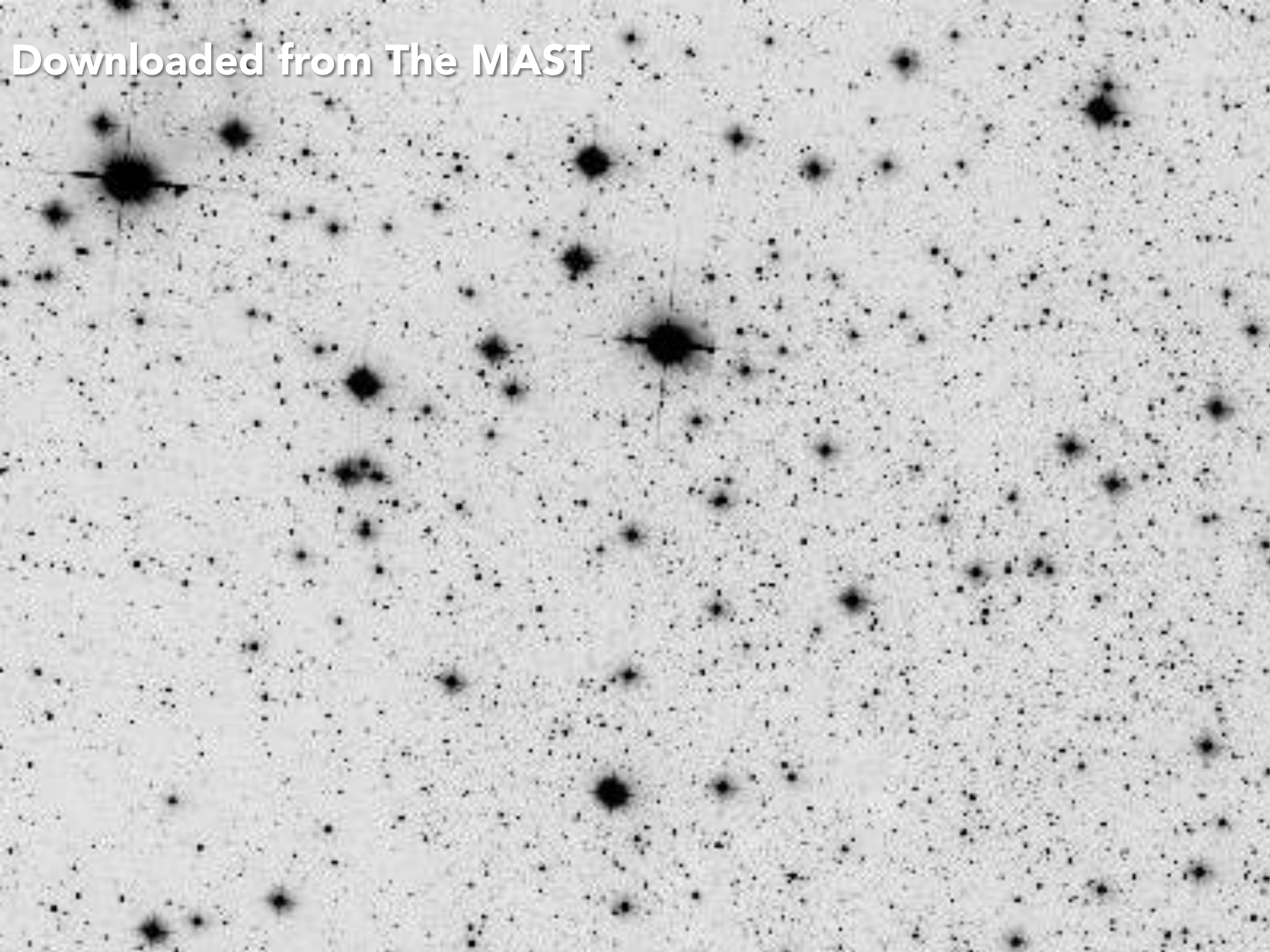
Two general issues.

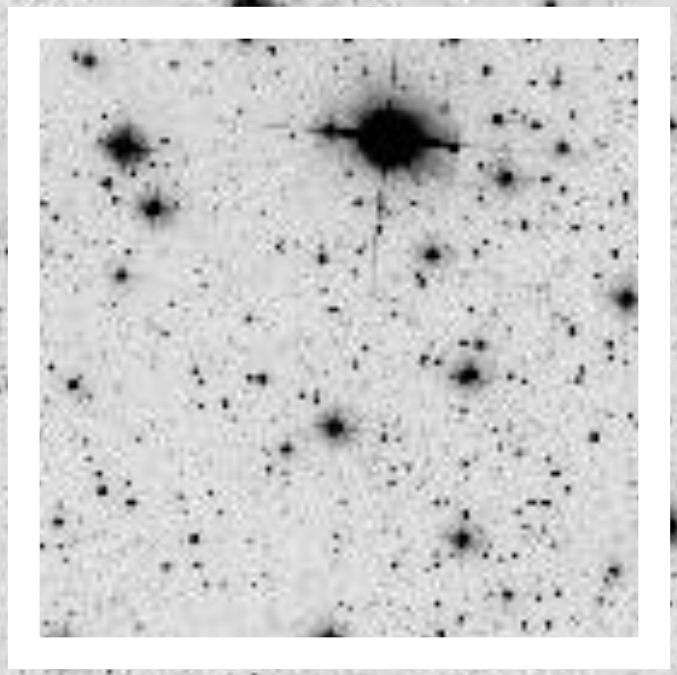
- Is there a signal above that consistent with noise?
  - Generally has not been an issue for microlensing.
  - Employ SNR thresholds considerably higher than random noise fluctuations.
- Is that signal actually due to a planet?
  - Astrophysical false positives have generally not been a concern.
  - Degeneracies have been more of an issue.
    - (timescale, model interpretation)
- However, false positives may well be more of an issue with WFIRST and K2.

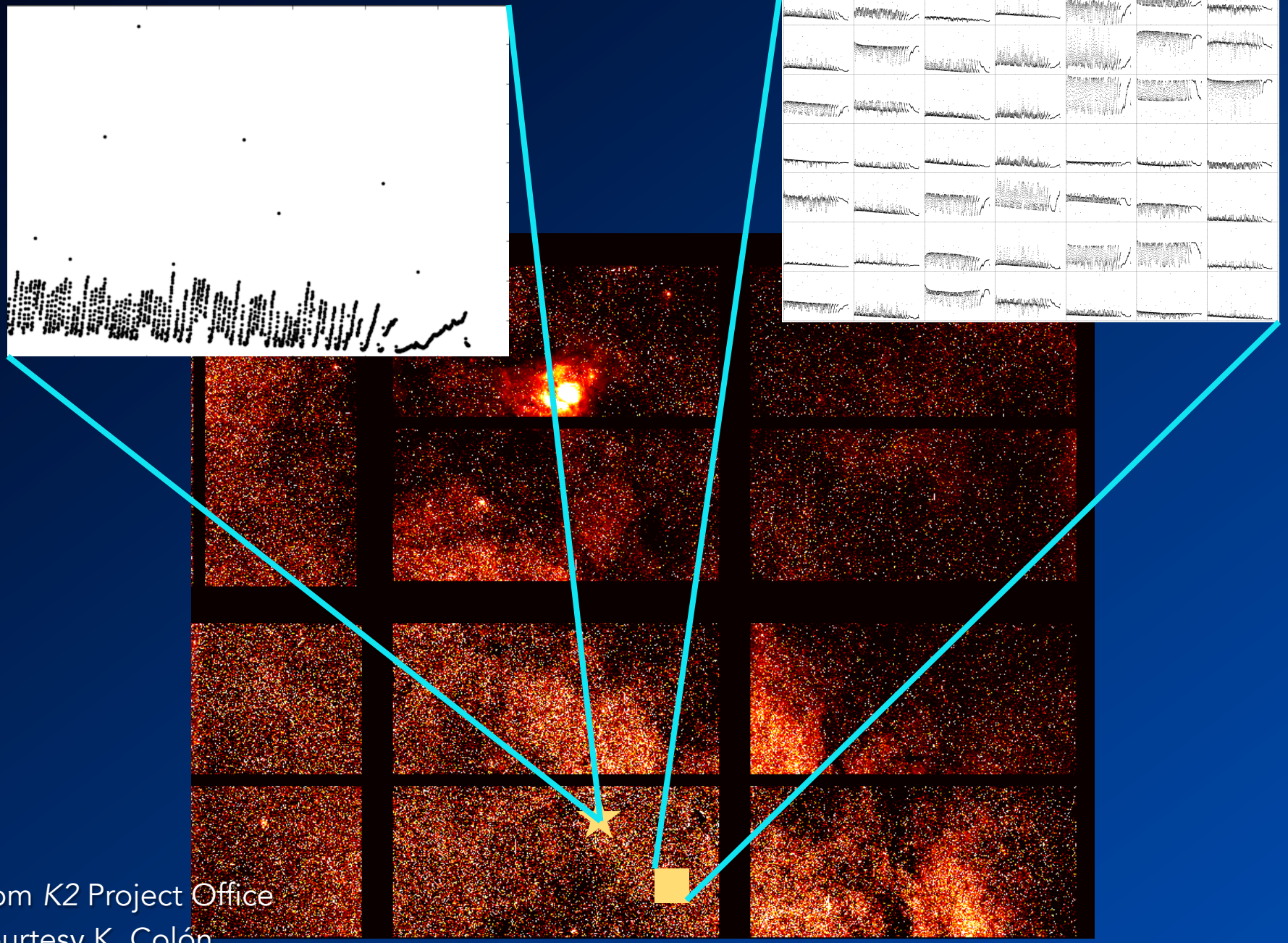
K2: Extracting Signals from Noisy Data Full of Systematics.



From *K2* Project Office
Courtesy K. Colón



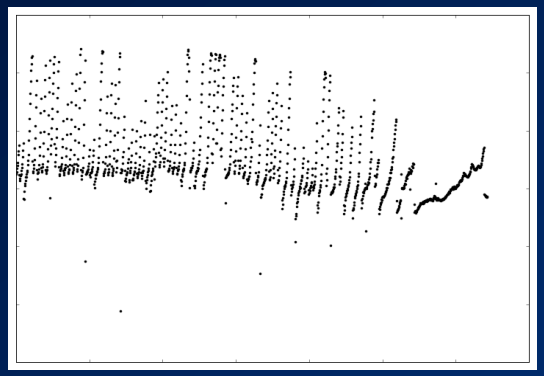




From *K2* Project Office
Courtesy K. Colón

Moving Forward – Photometry Challenges: *Kepler* Event Recovery

Causal Pixel Model



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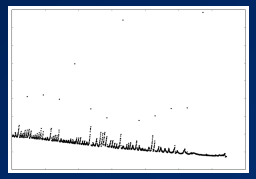
Input pixels



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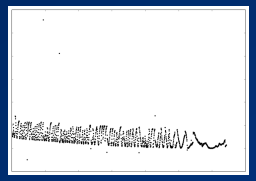

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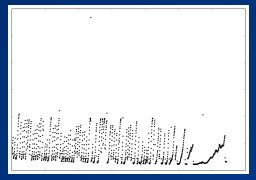

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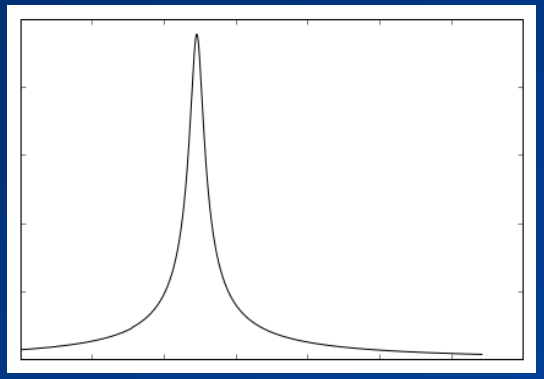
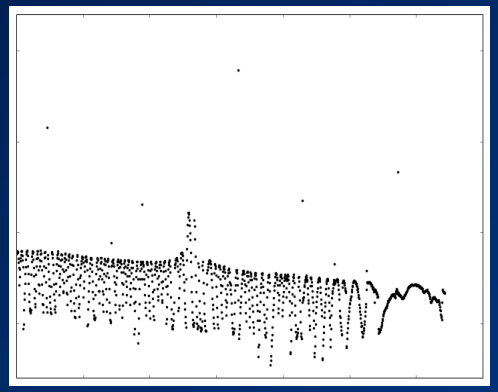
Microlensing Model



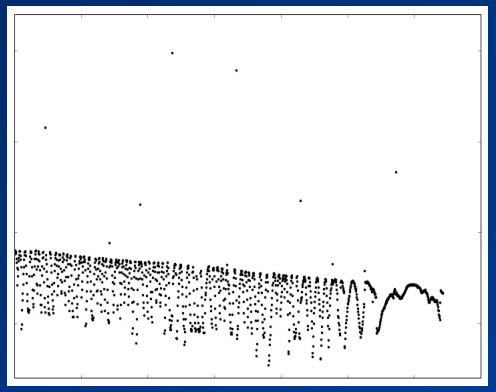
Moving Forward – Photometry Challenges: *Kepler* Event Recovery

Dun Wang
Graduate Student, NYU

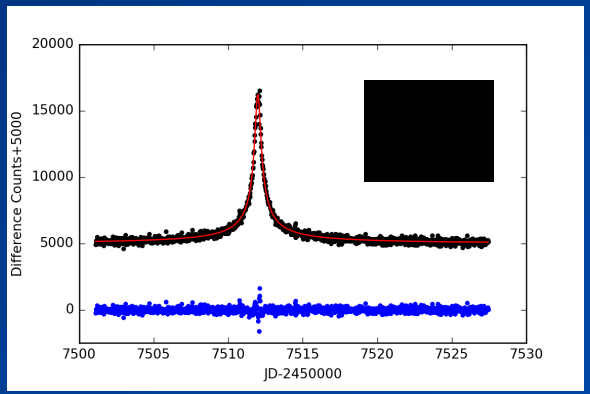
Raw Pixel Light Curve
(i.e., data!)



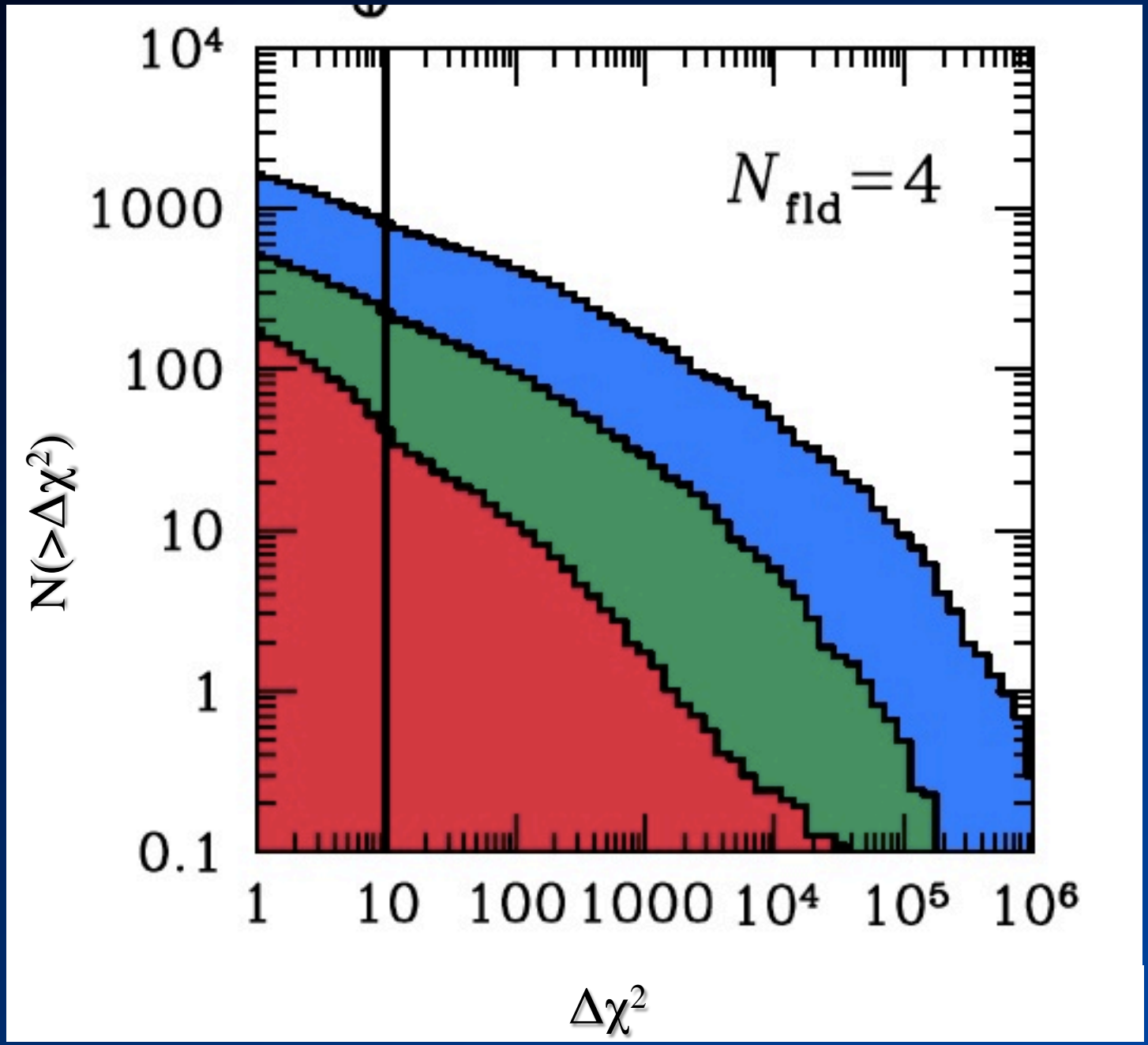
Causal Pixel Model



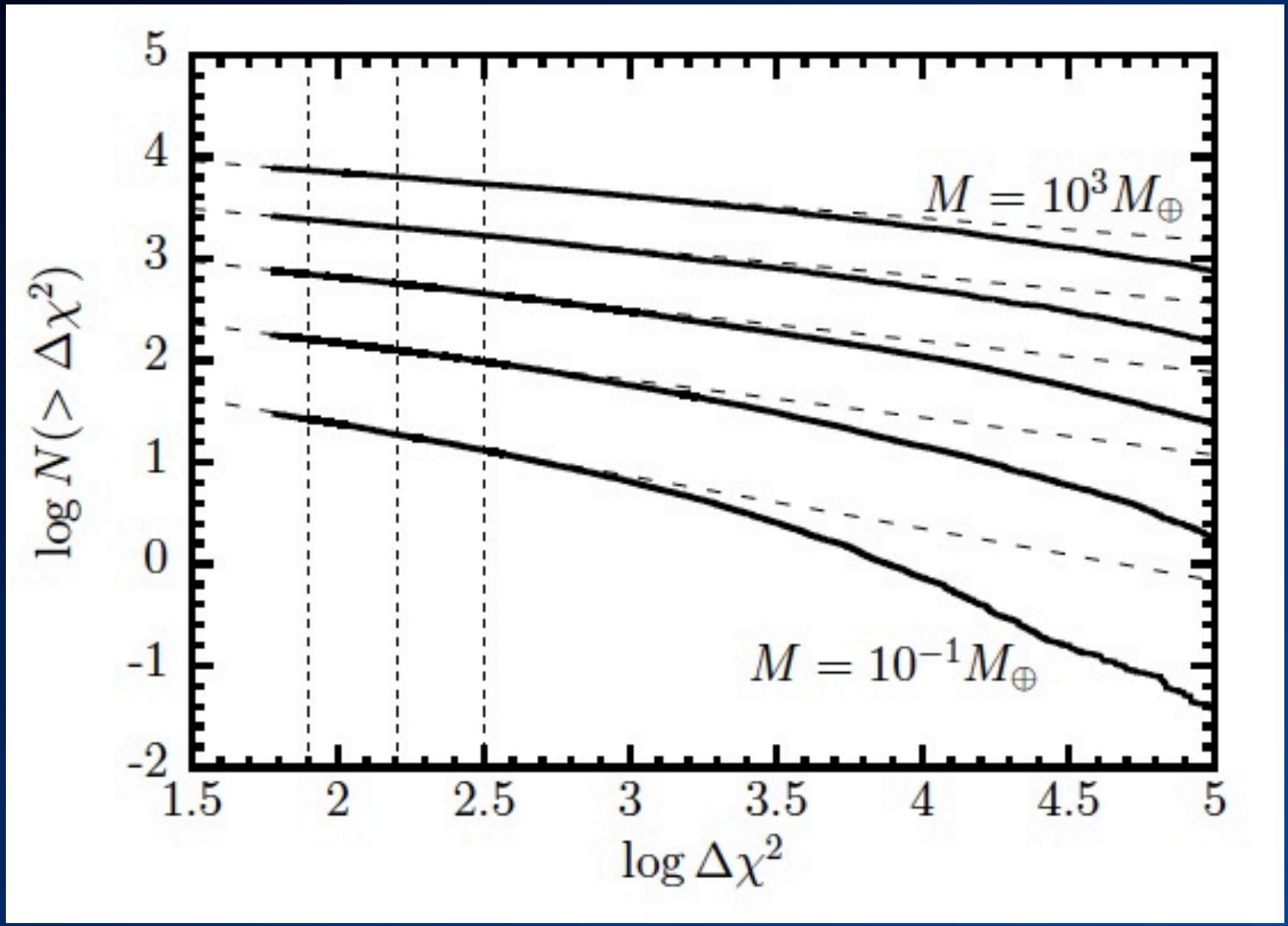
Output light curve!



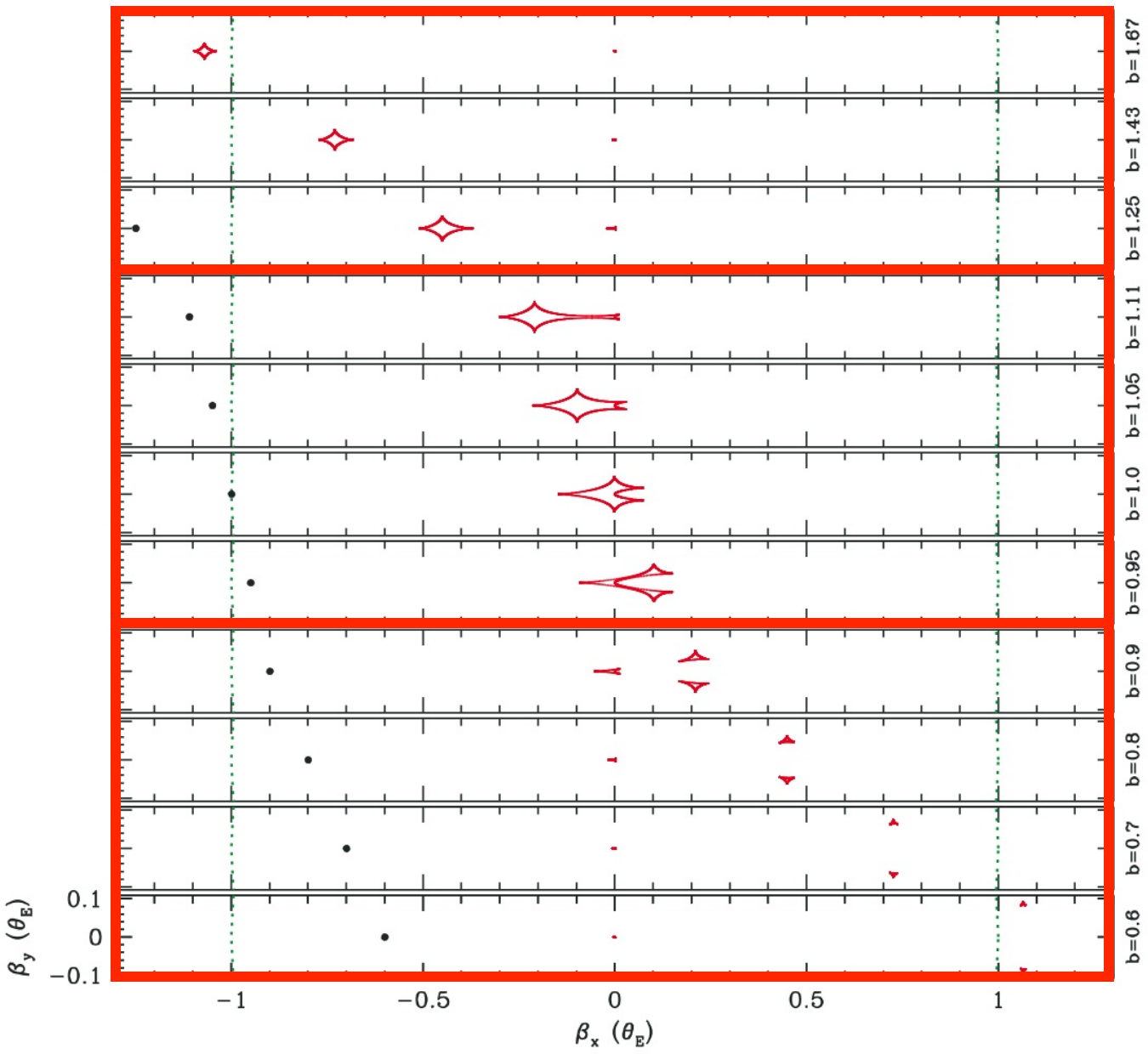
WFIRST:
What happens when we have whit(er) noise and can dig into deeper into the data?



(Henderosn et al. 2015)



(Penny et al. 2016, in prep)



Wide:

- Two caustics
- Central/ Planetary

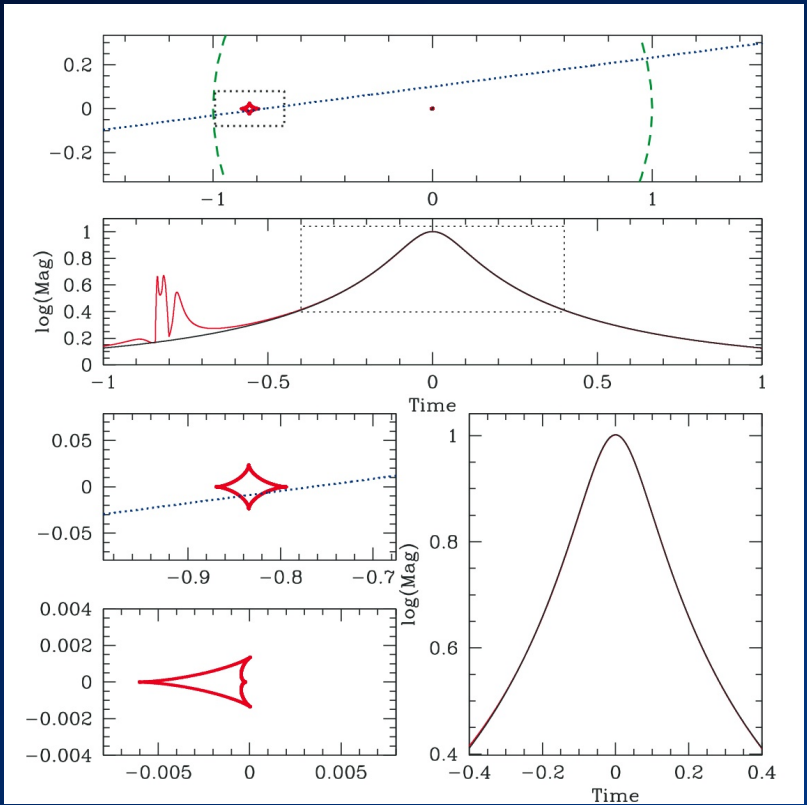
Intermediate or resonant:

- Narrow range around d~1
- Large caustics

Close:

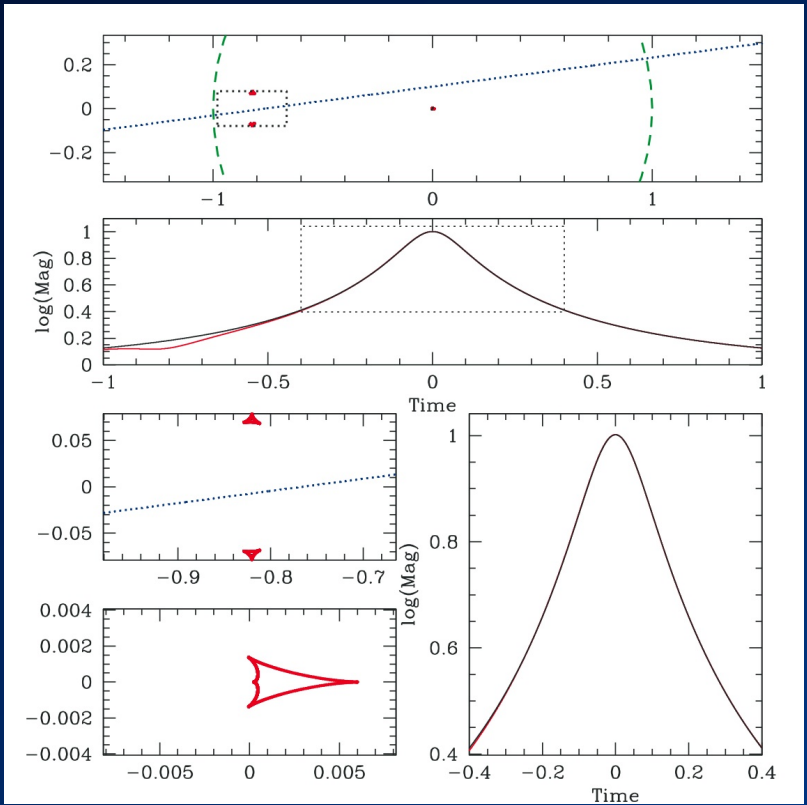
- Three caustics
- Central
- Two planetary

Planetary Caustic Perturbations



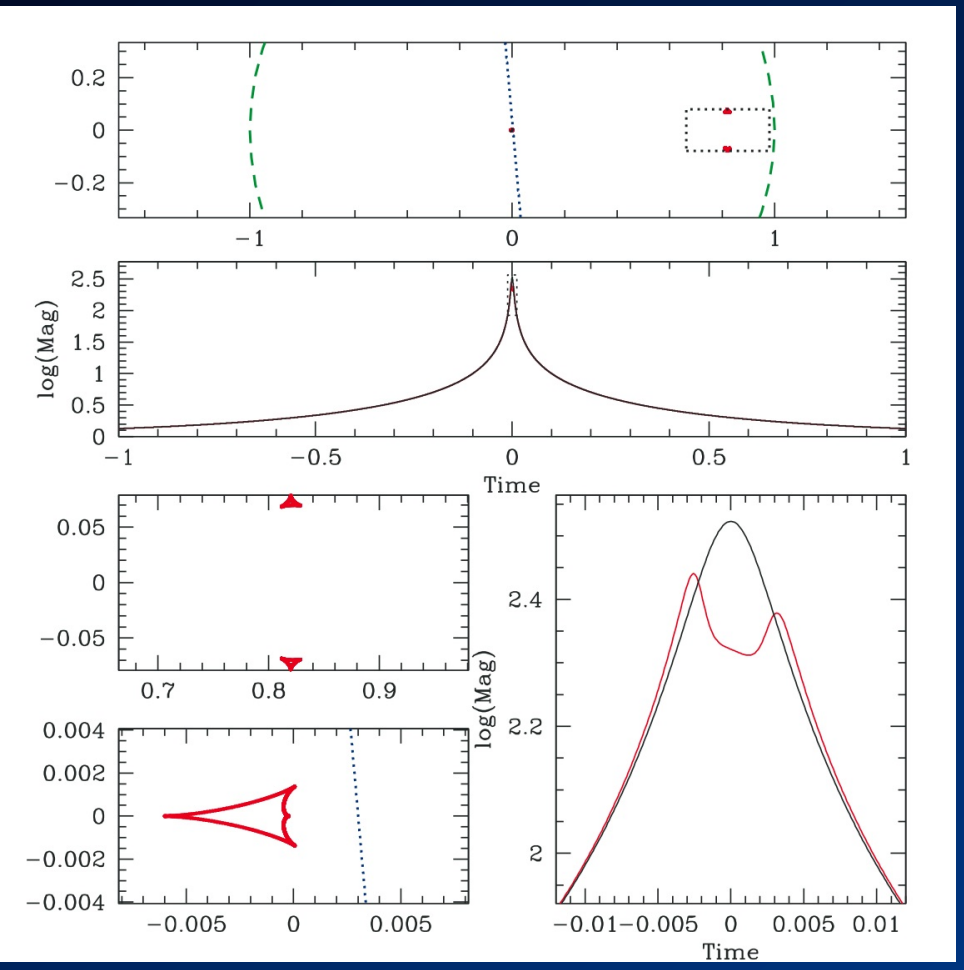
- Can happen anywhere, but usually on wings
- Unpredictable.
- Size of caustic is proportional to $q^{1/2}$
- For d>1, perturbations are mostly postive
- Size of caustic is proportional to d^{-2}

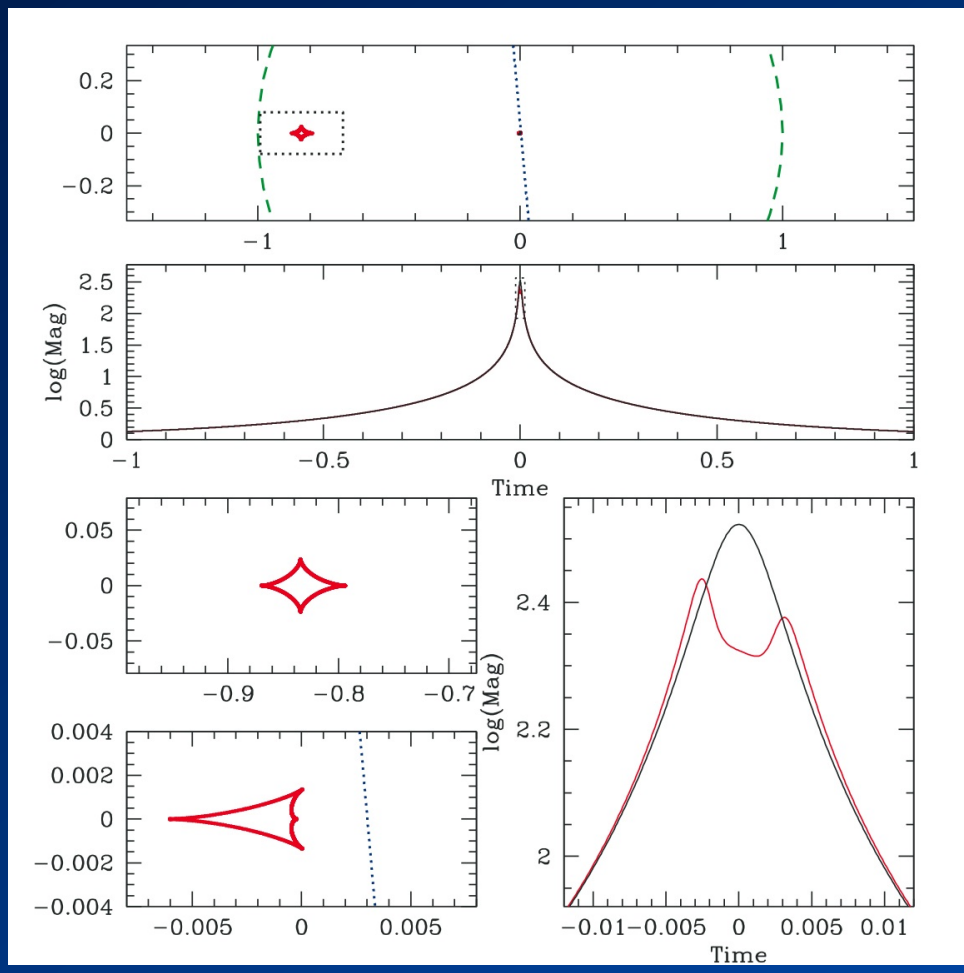
Planetary Caustic Perturbations



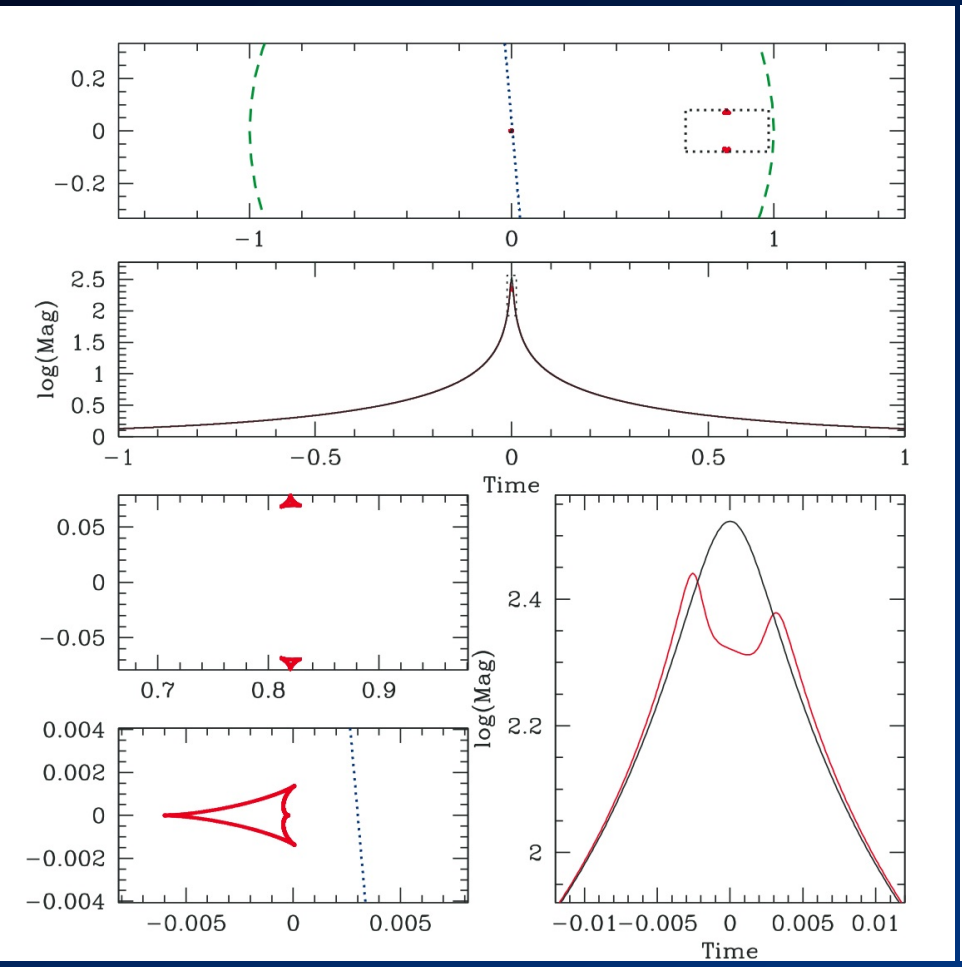
- For d<1, perturbations are mainly negative.
- “Trough” of demagnification between the triangular caustic.
- Size of caustic is proportional to d^2
- For $d \rightarrow 1$ the trough becomes deeper.

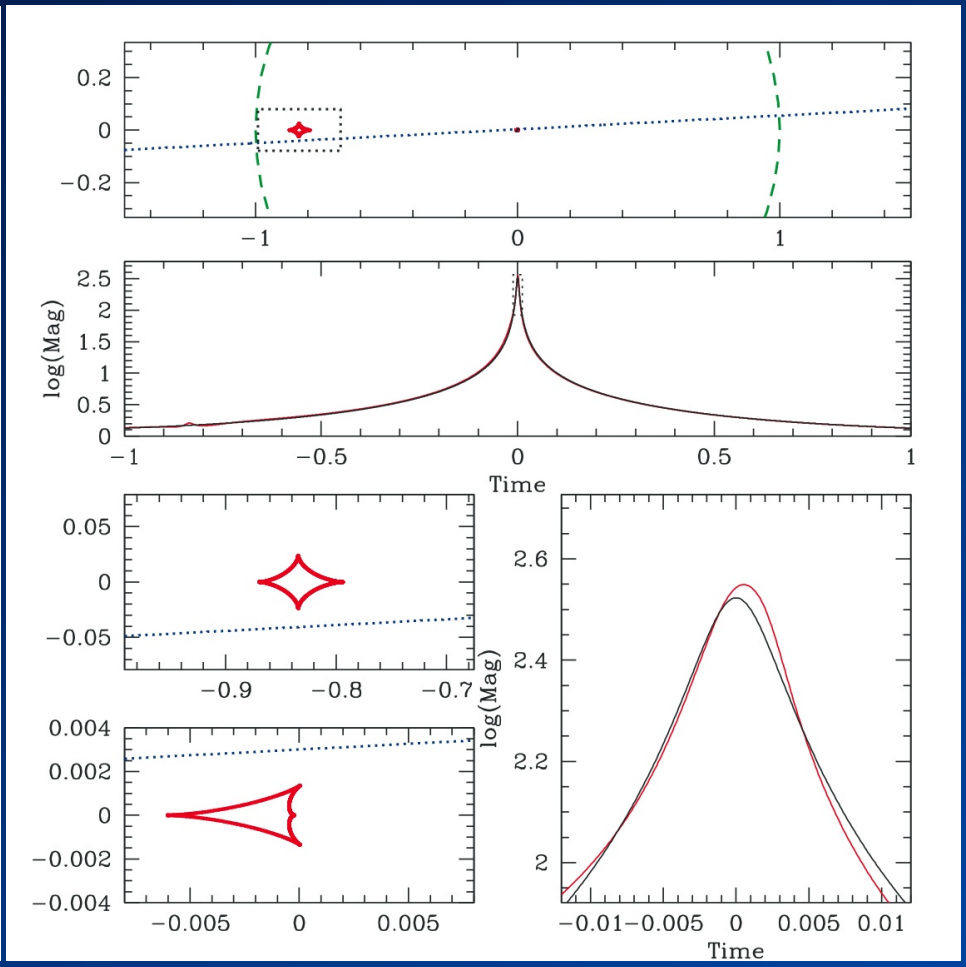
$d \leftrightarrow d^{-1}$ close/wide degeneracy



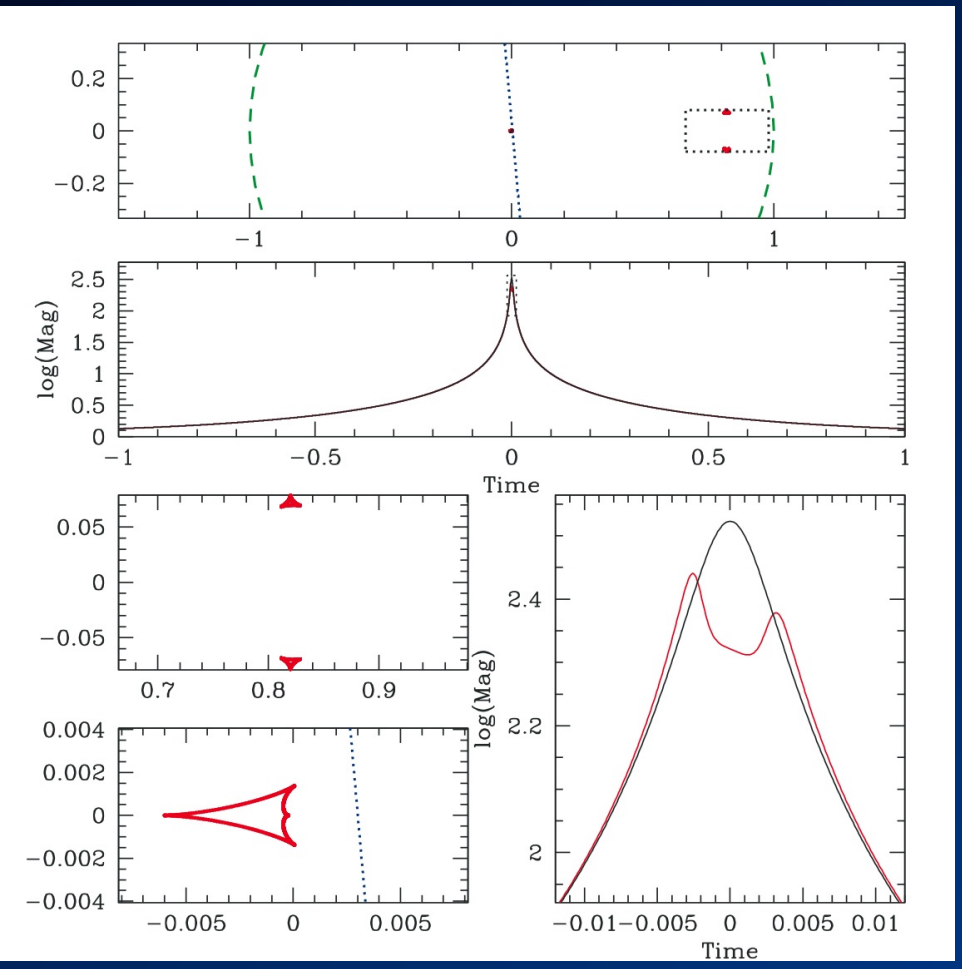


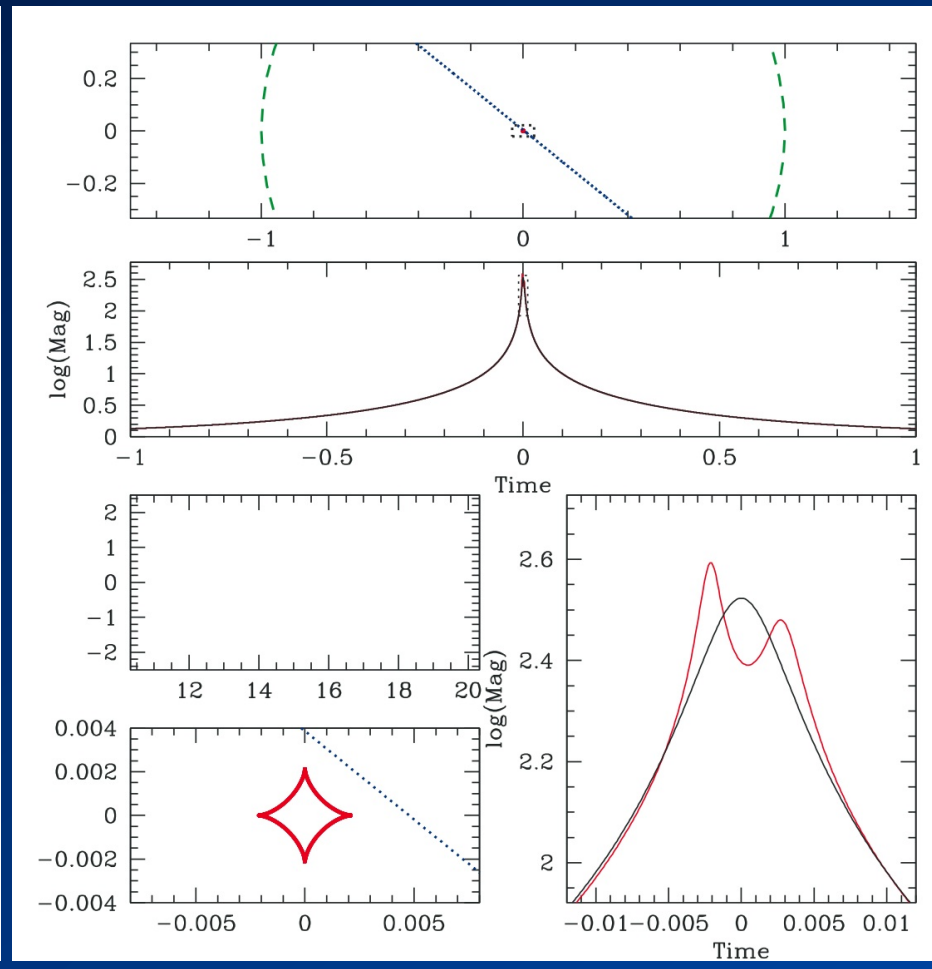
Perturbations Small Along Axis

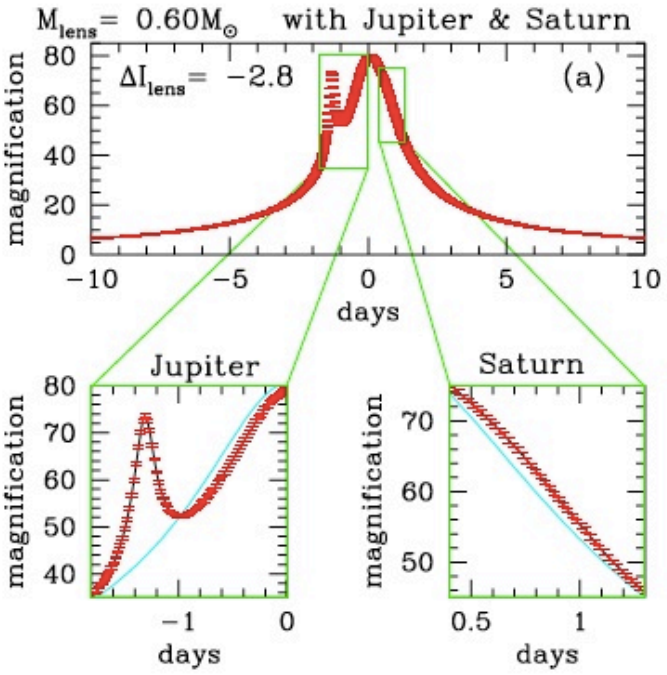


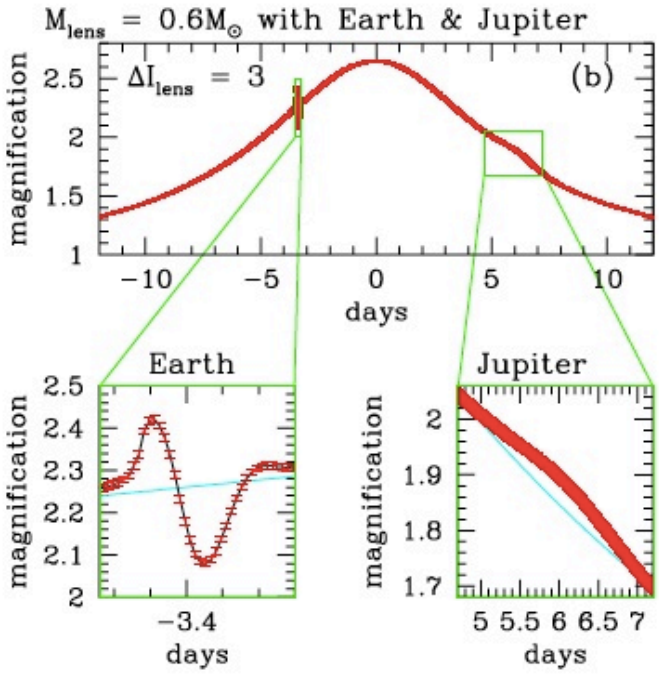


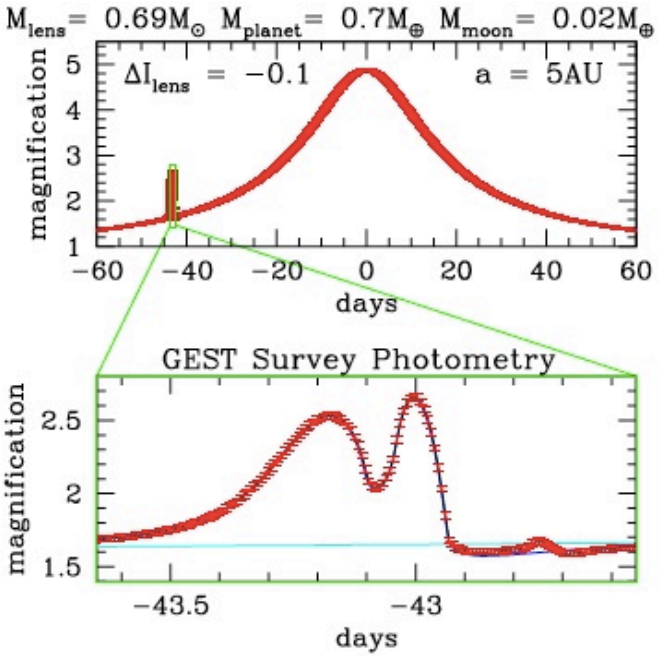
Extreme Binaries versus Planets

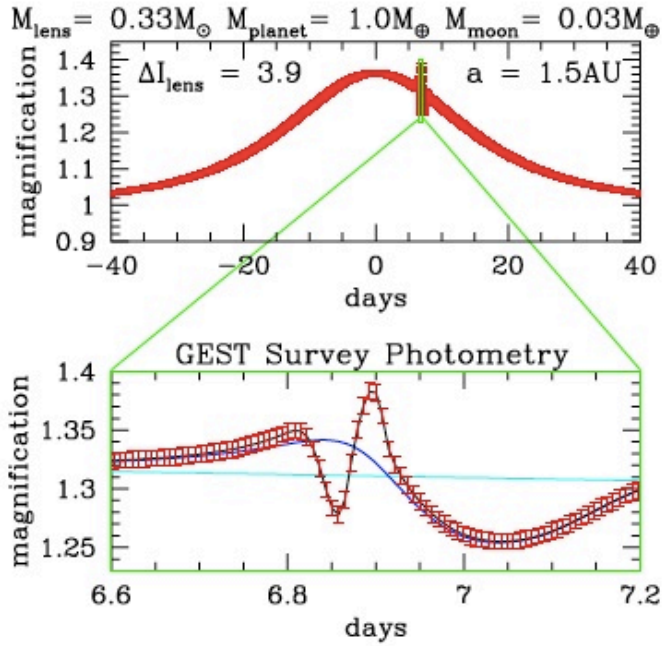












(Bennett & Rhie 2002)

Summary.

- Microlensing is currently experiencing a watershed (thanks NWNH!).
- K2 will confirm (or refute) the existence of a large population of free floating planets.
- WFIRST will complete the census begun by *Kepler*, and will revolutionize our understanding of cold planets.
- WFIRST will enable qualitatively new, exciting science: sub-Earth-mass planets, free-floating planets, outer habitable zone planets, mass measurements.
- While false positives have generally not been a concern for microlensing surveys, they will likely be more important for K2 and WFIRST.
- We will need to think carefully about how to extract low SNR signals from the exquisite WFIRST data.

Short Duration Deviations in the Wings