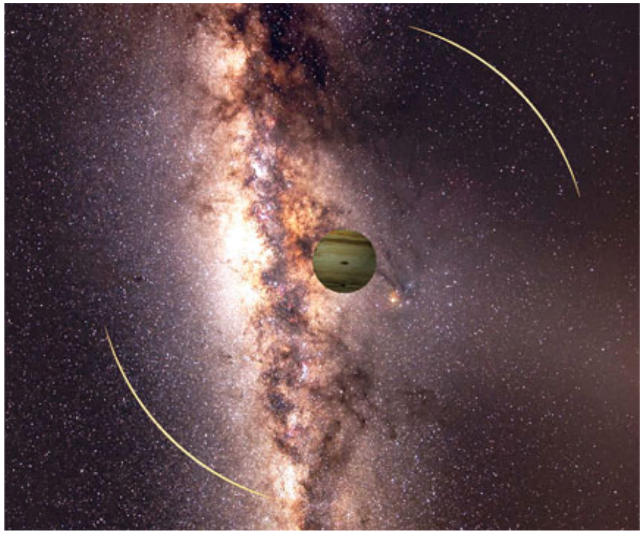
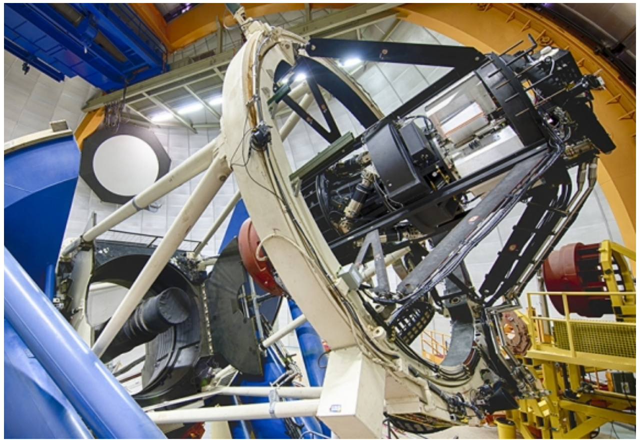
Measuring the Free-Floating Planet Mass Function with K2 & DECam





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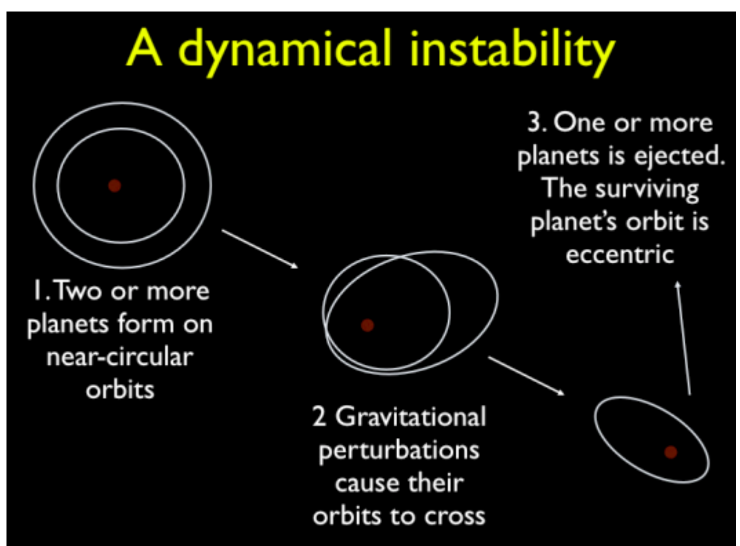
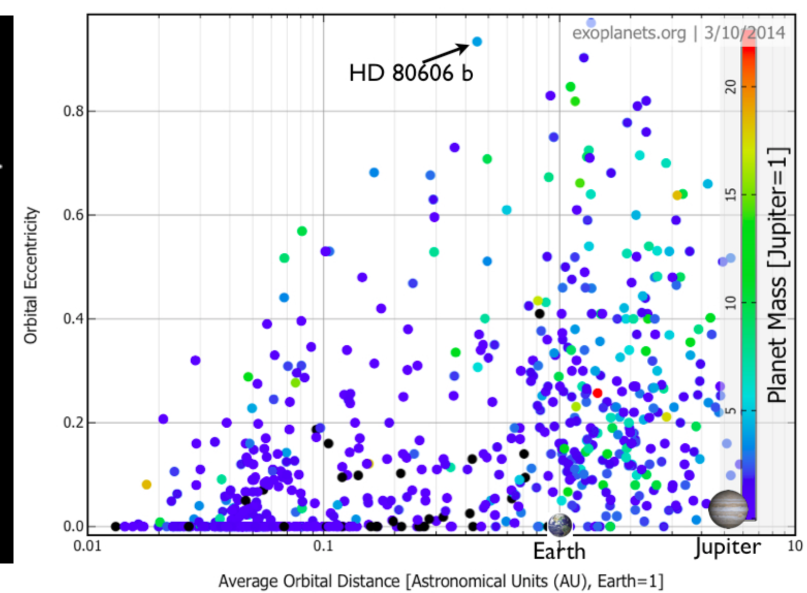
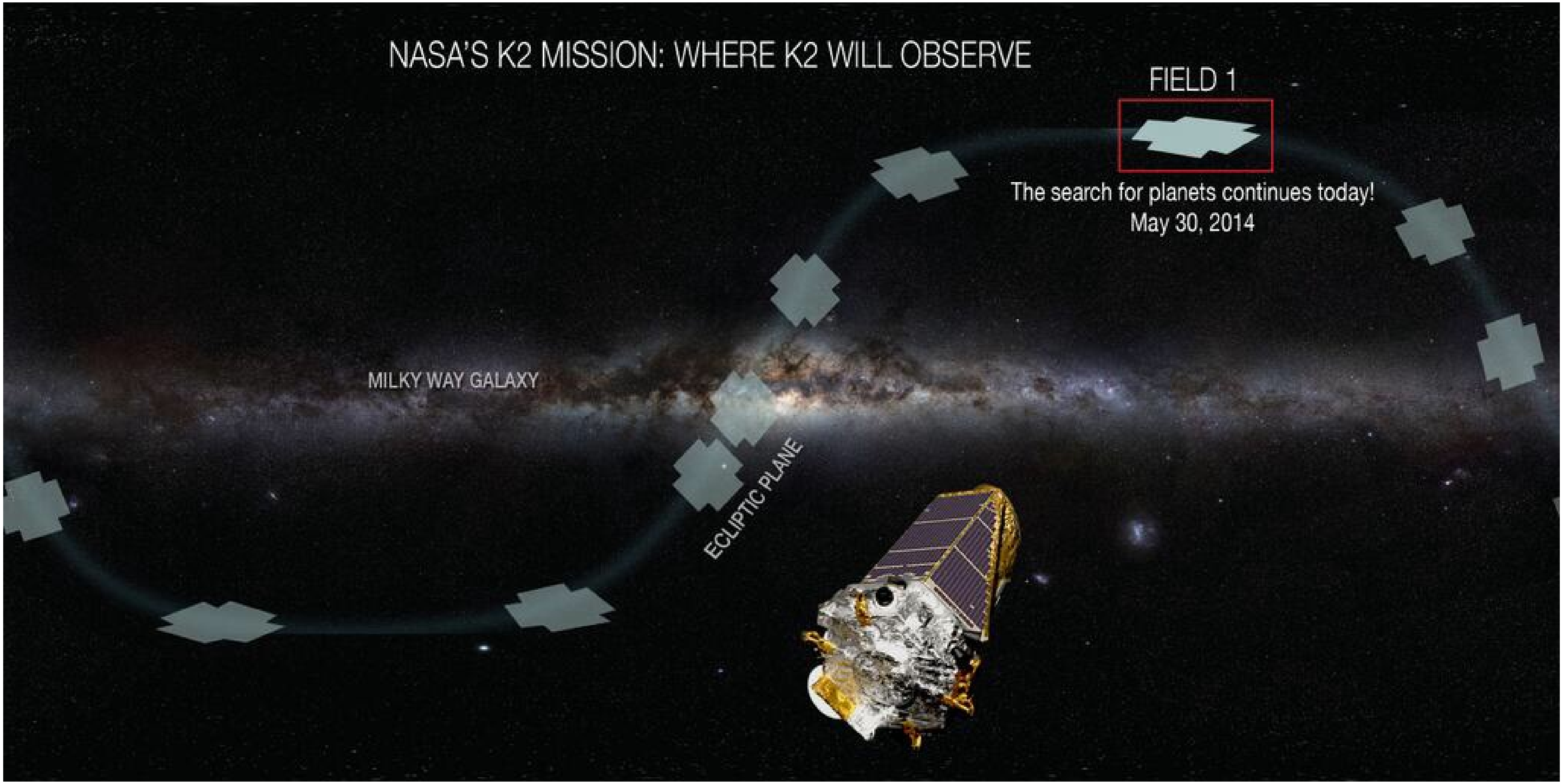
Free-Floating Planets

- Planets without host stars
- Probably form in low numbers as failed stars
- More probably formed through ejections of planets after protoplanetary disk dissipation
- **Their mass distribution bears the fingerprints of the formation and subsequent evolution of planetary systems**
- **K2 offers a one-time opportunity to measure their masses**

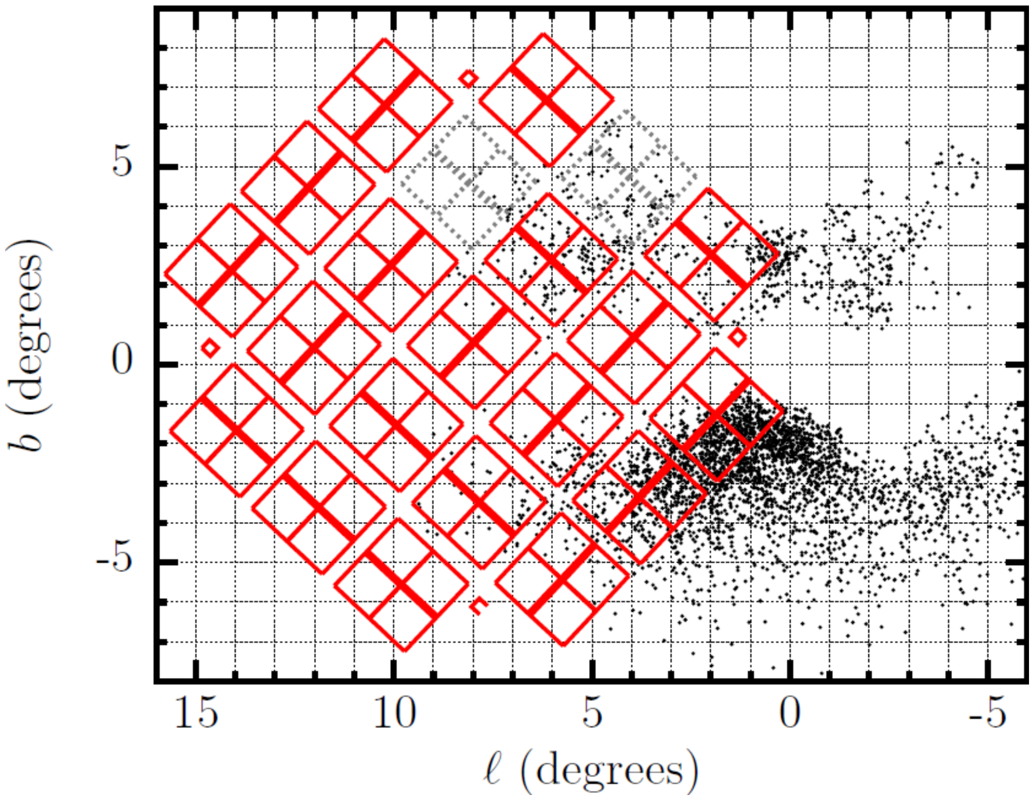


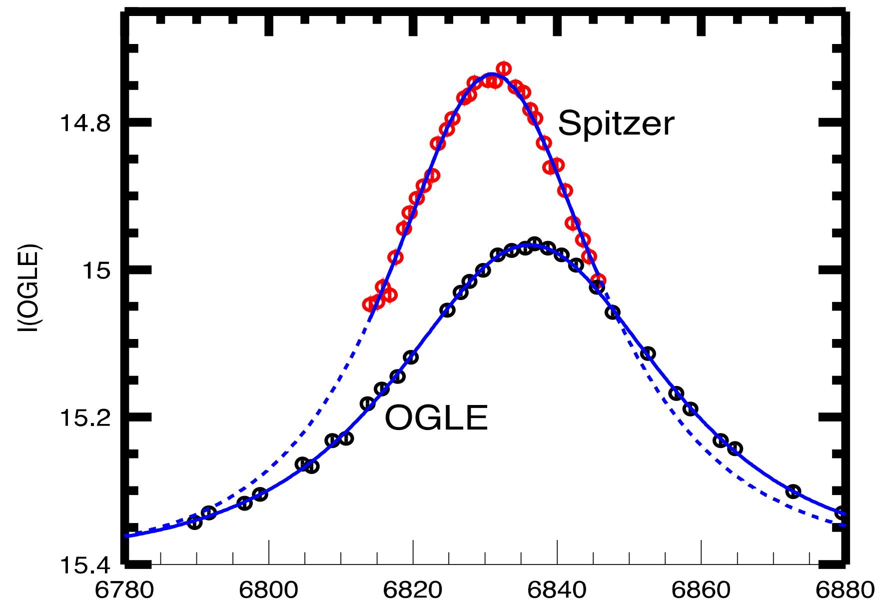


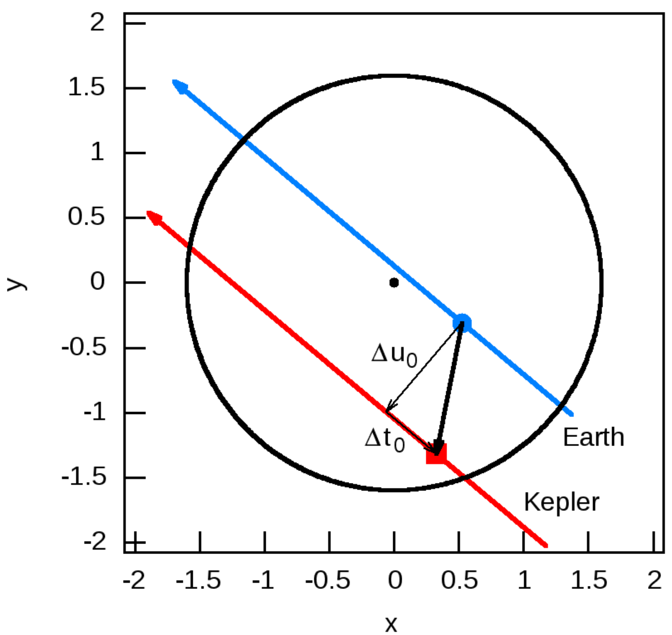
The K2 mission



K2 Campaign 9

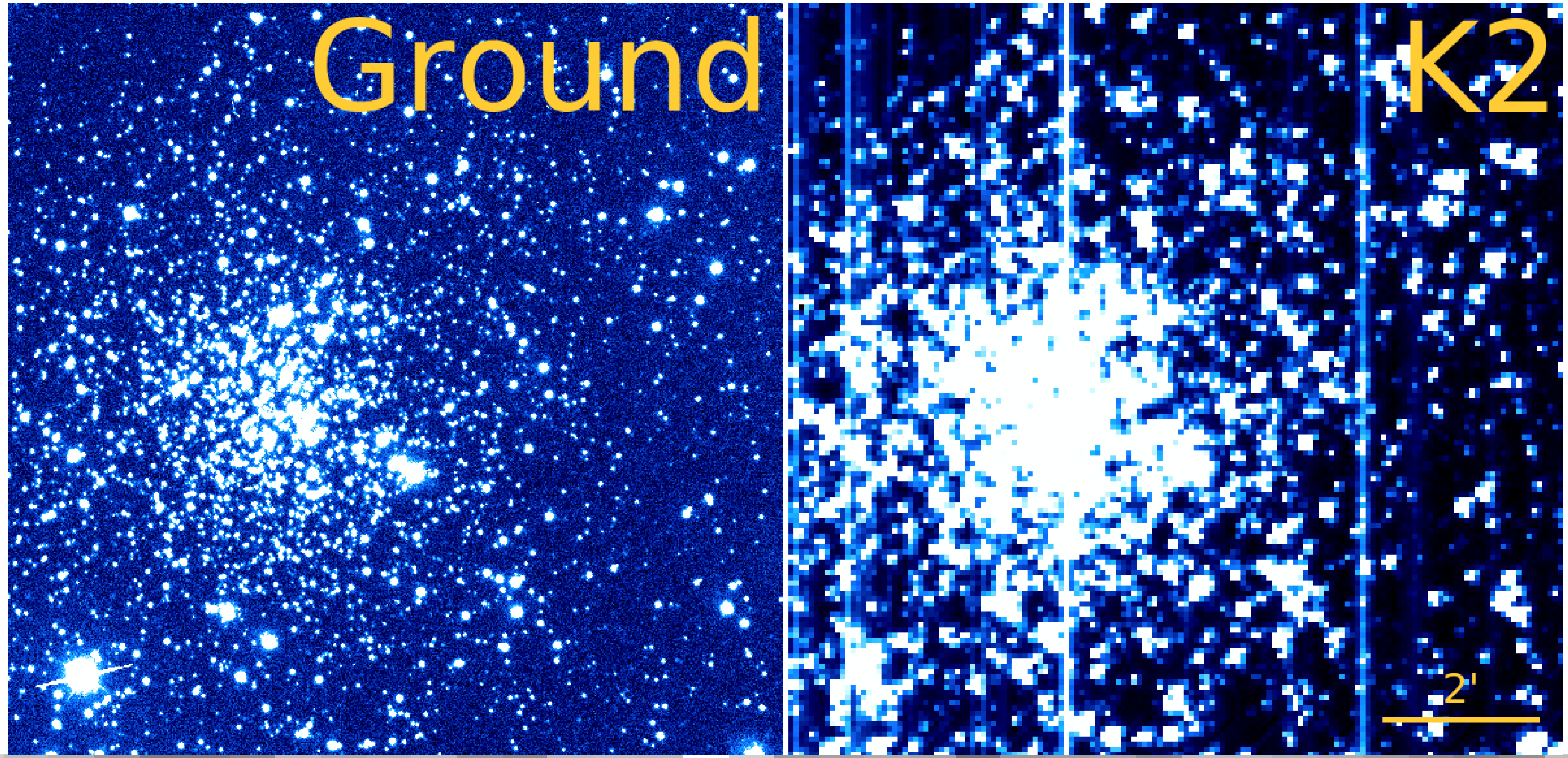


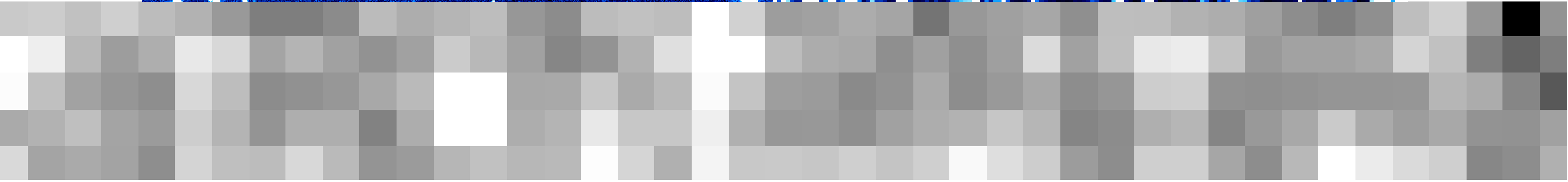


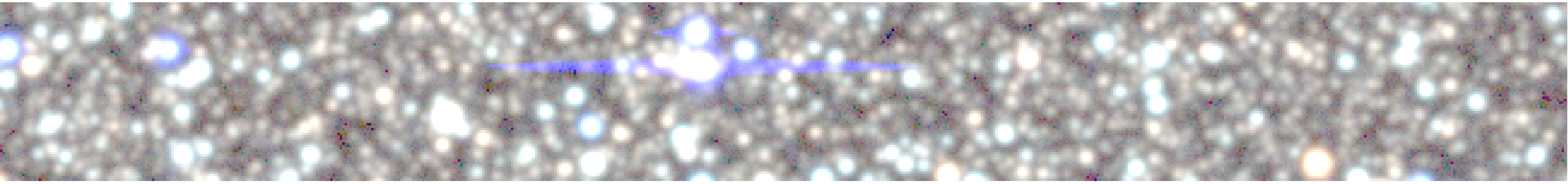


- 80+ day campaign Apr-Jun 2016
- Target Galactic Bulge to search for microlensing, ~5 sq deg
- Earth-K2 parallax baseline enables mass and distance measurement of stars and planets

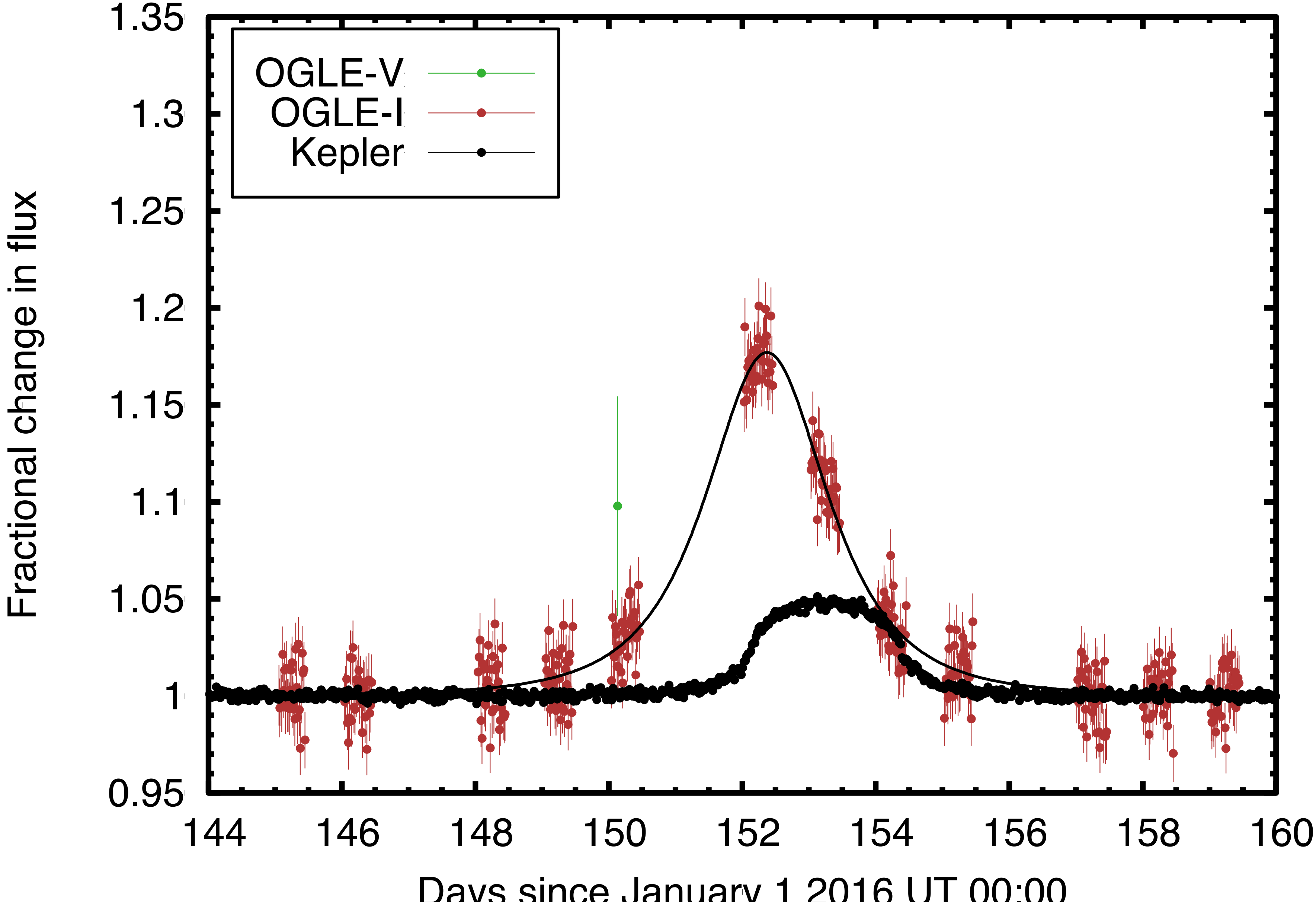
Simulating K2





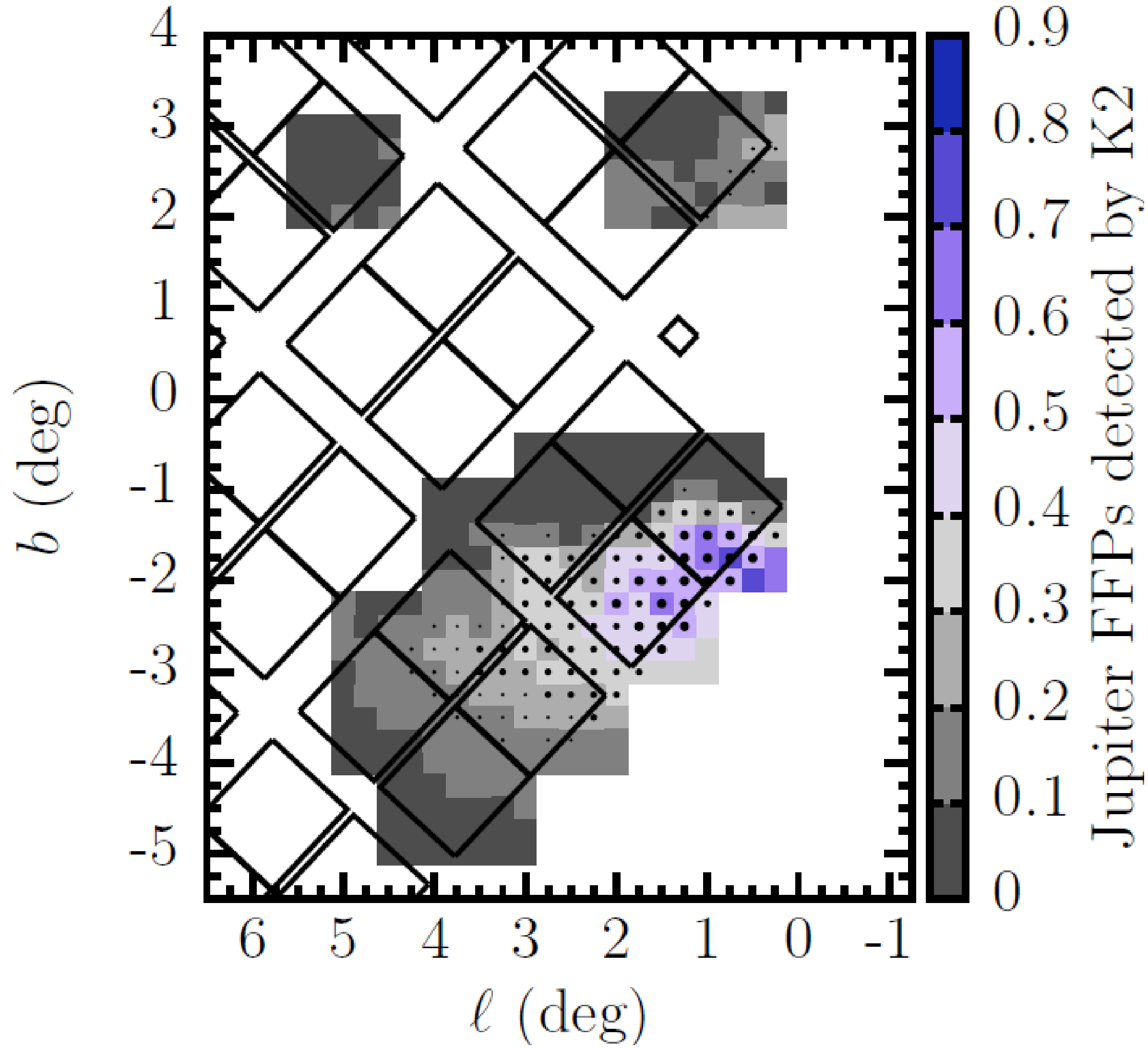


Simulating K2



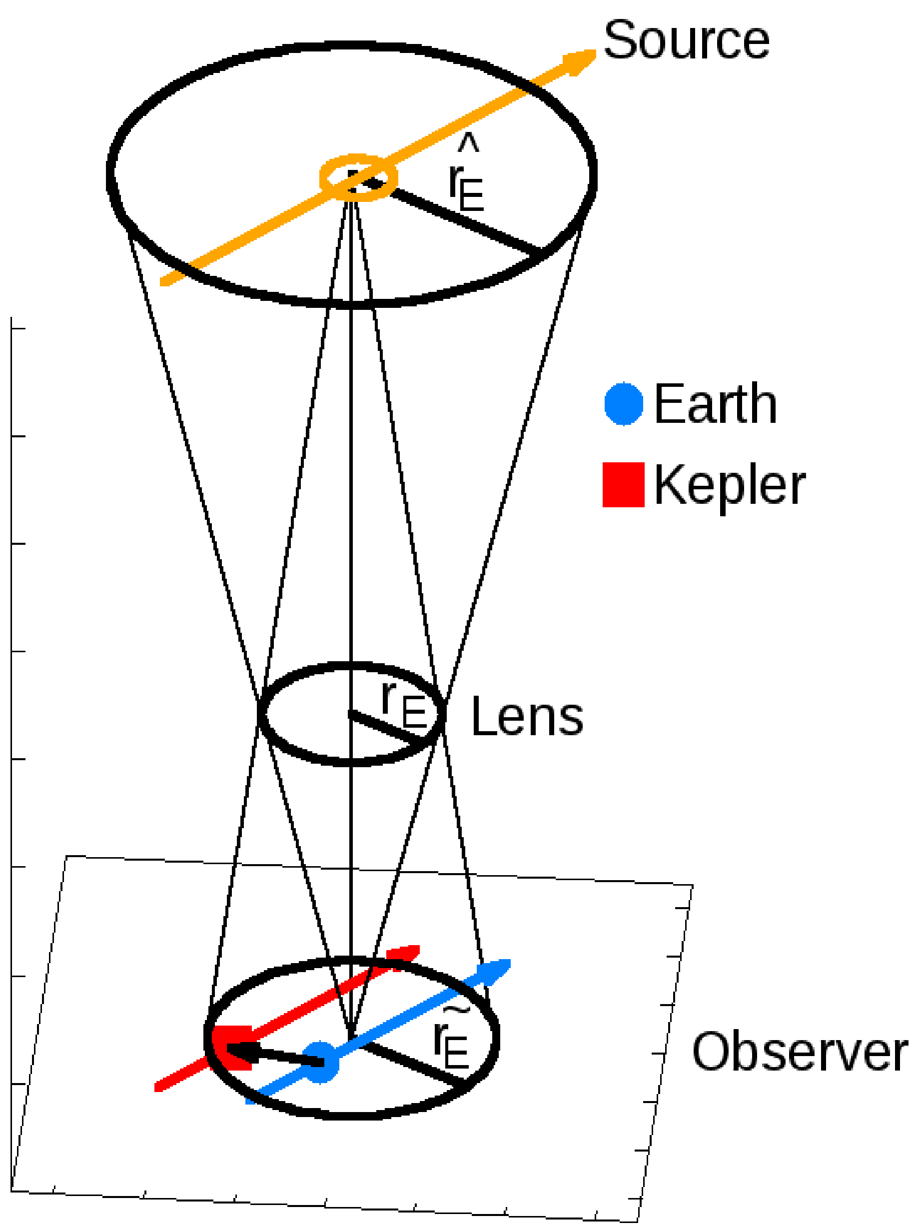
K2 Campaign 9

Mass (M_E)	Detections K2
1000	3.5
300 (Jupiter)	6.5
100 (Saturn)	11.9
Total	22

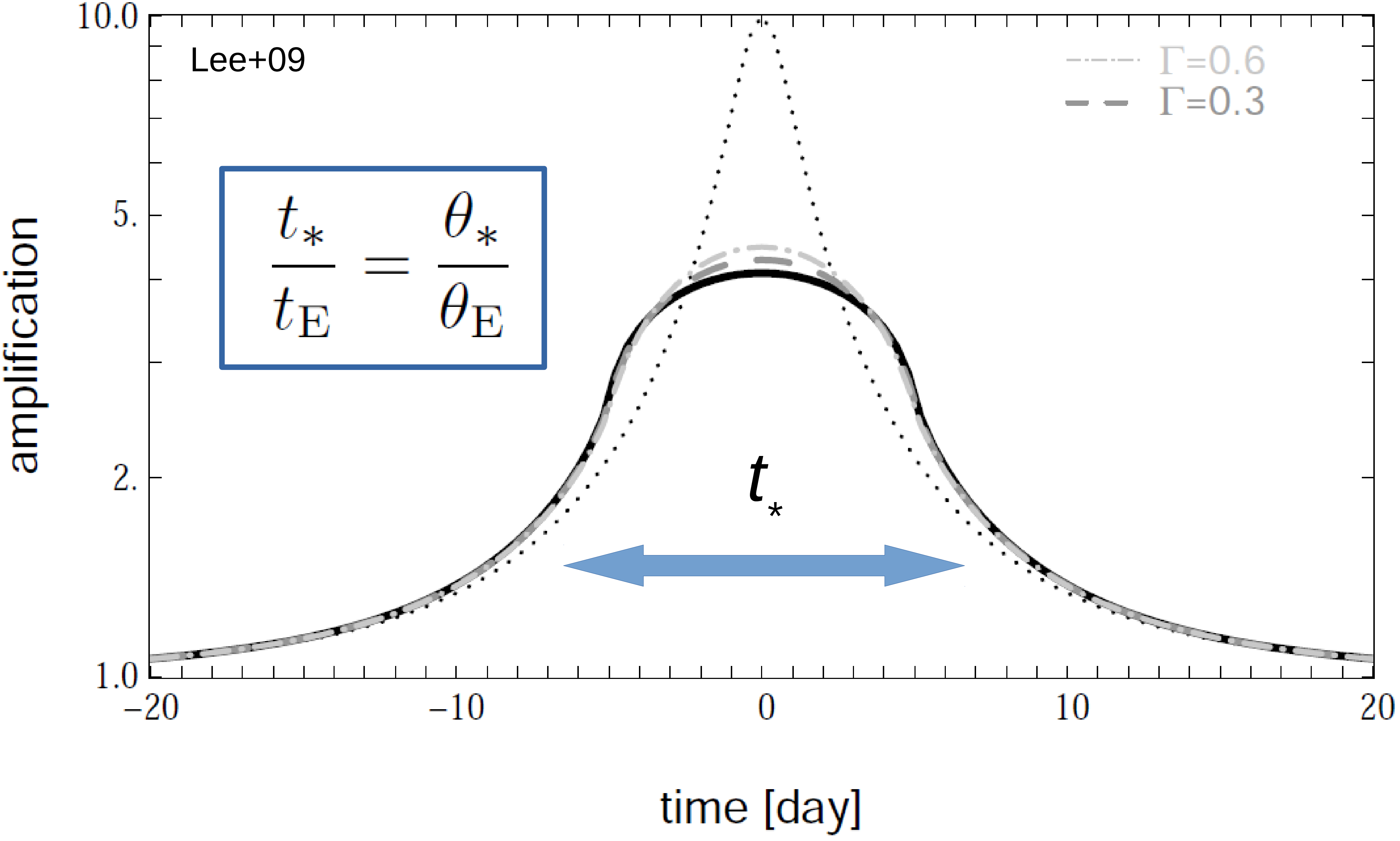


How to measure the mass of a free-floating planet?

Parallax & Angular Einstien Radius



Finite Source Effects



$$\frac{t_*}{t_E} = \frac{\theta_*}{\theta_E}$$

Finite Source Effects

Known

Angular Diameter
Knowable

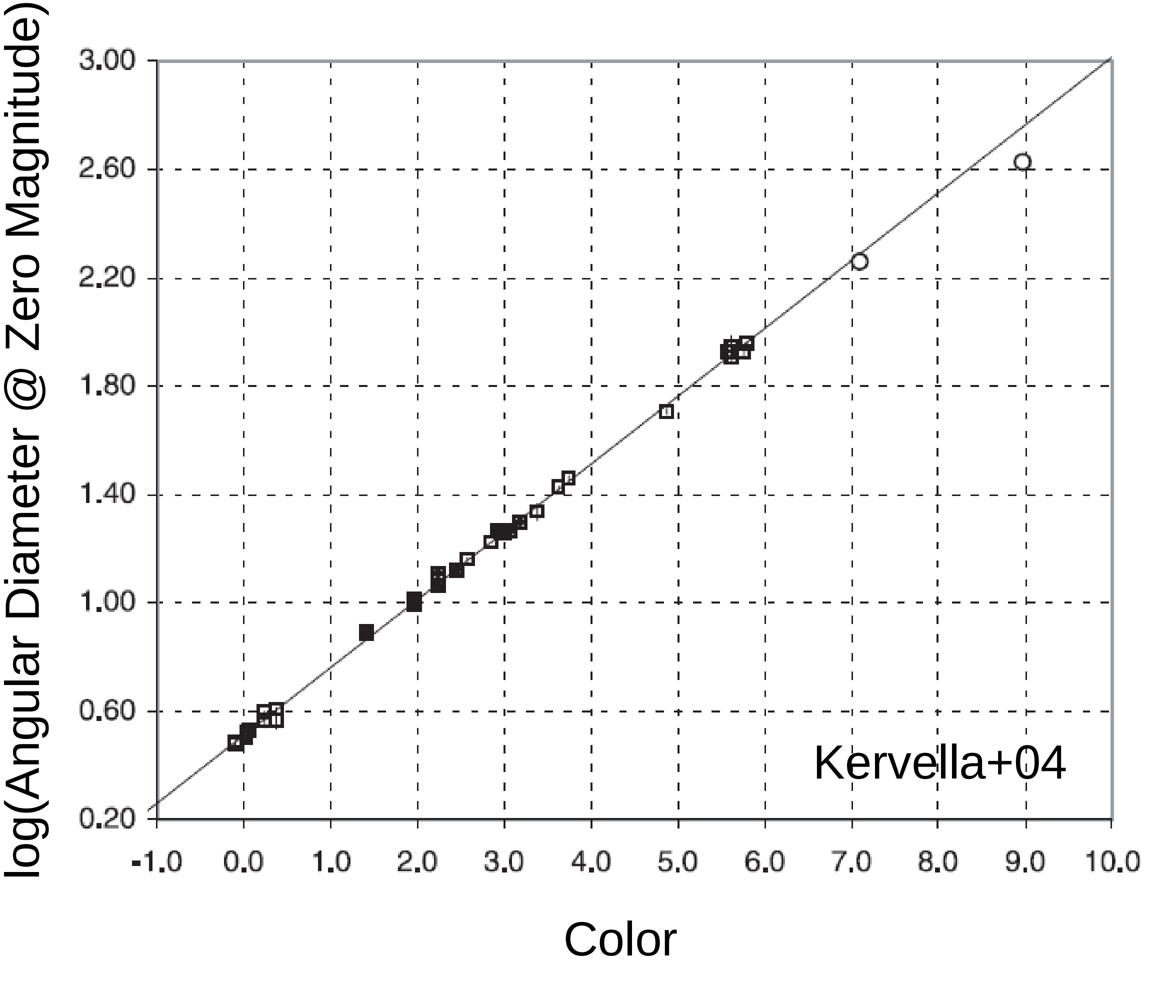
$$\frac{t_*}{t_{\mathrm{E}}} = \frac{\theta_*}{\theta_{\mathrm{E}}}$$

Known

Unknown

Surface Brightness-Color Relations

Measuring the color and extinction gives you the angular diameter of the source



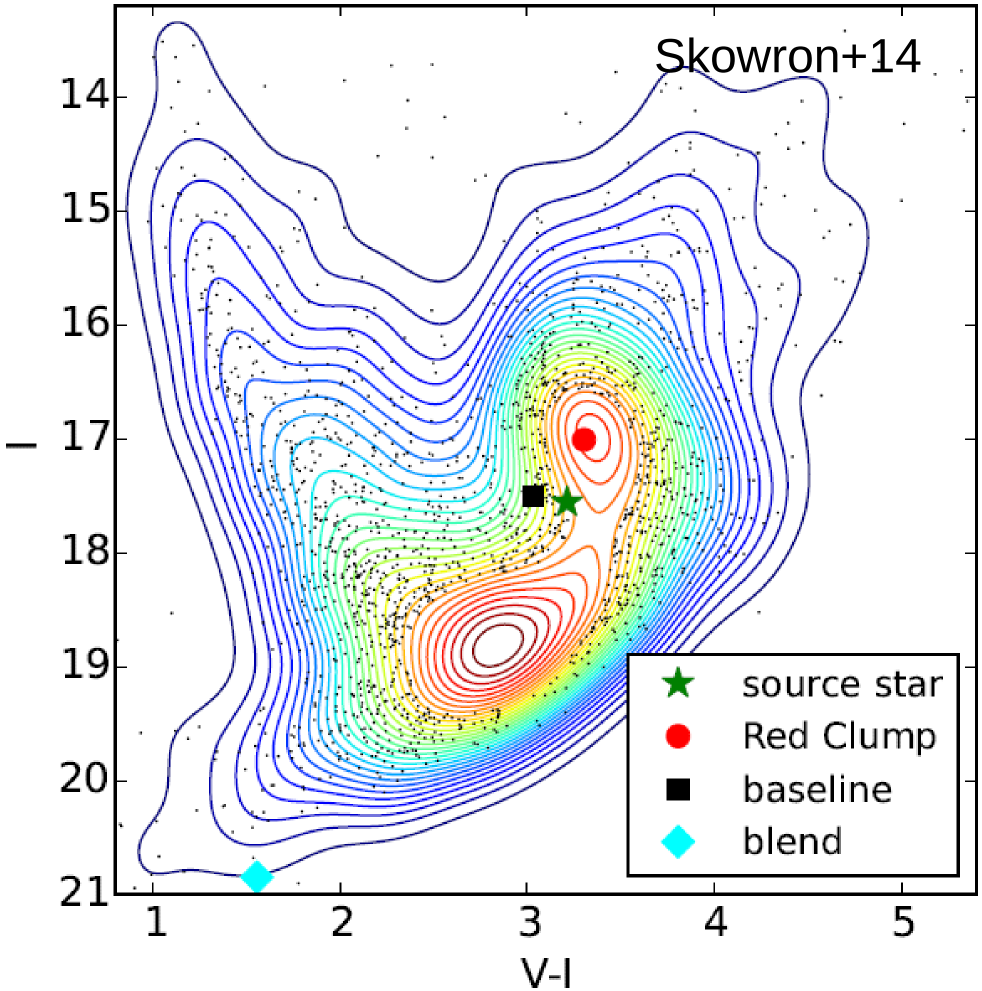
e.g.

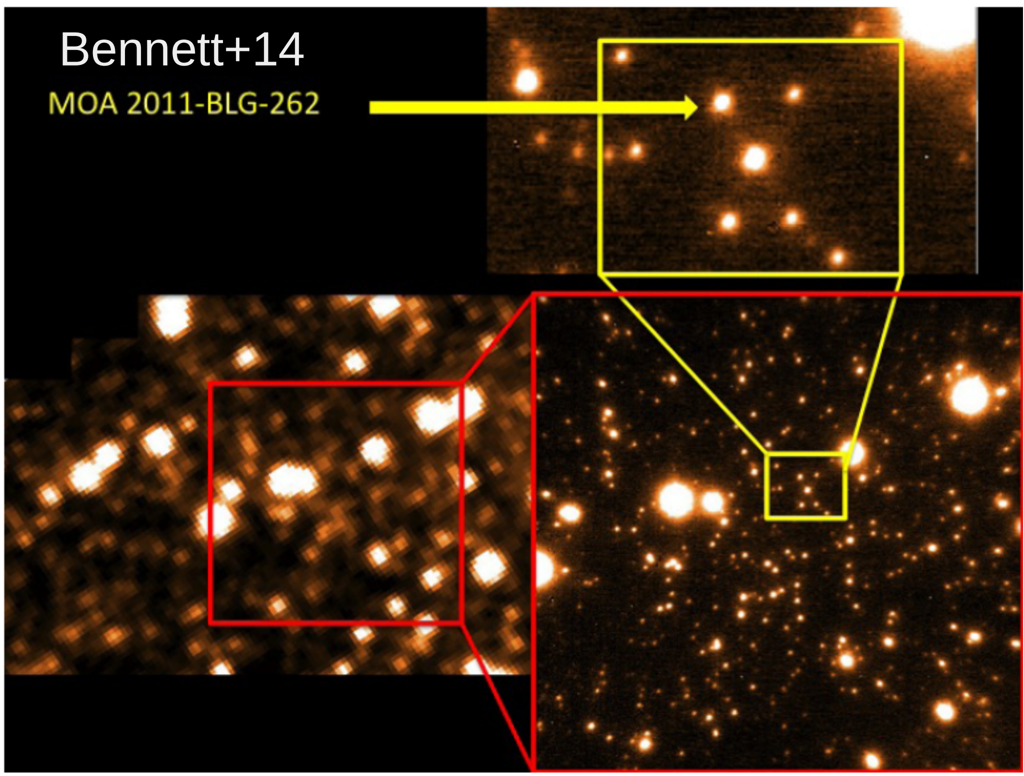
$\log \theta_{LD} = 0.0755\,(V\text{-}K) + 0.5170 - 0.2\,K$

Other relations for other colors

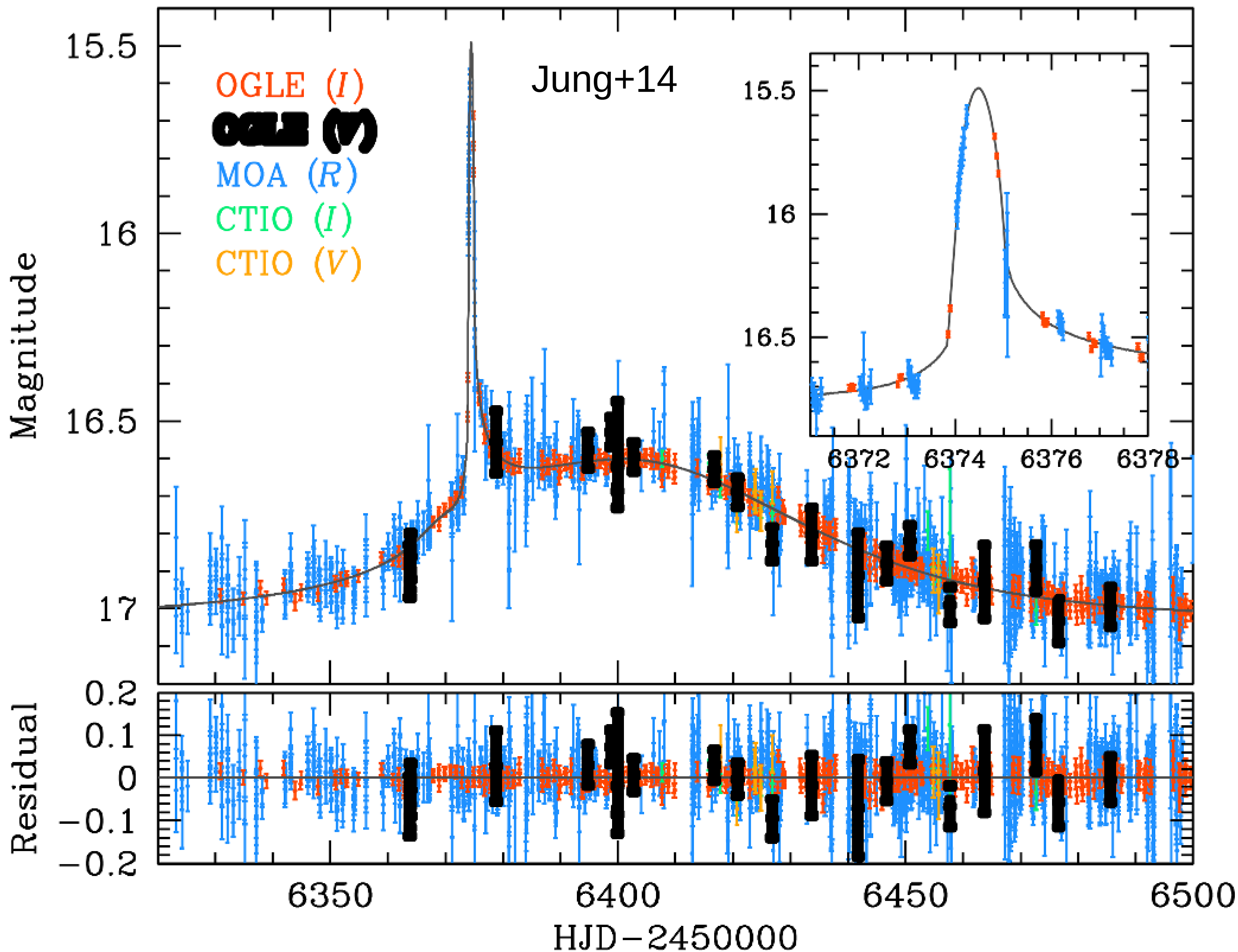
But you must isolate the source

This requires measuring the color of the source ***while it is magnified***





Current Source Color Measurements



For Free-Floating Planets

There Is No Follow-up

Color in Free-Floating Planet Events

- Color cadence needs to be almost as frequent as the main survey observations
- Can we achieve this from the ground?

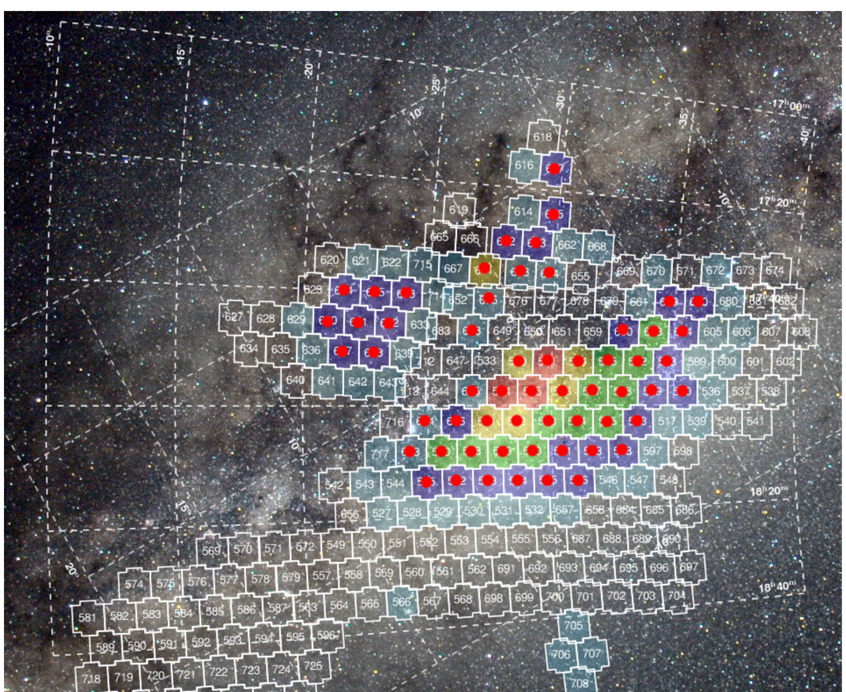
Typical timescales

Jupiter (300 M_{earth})	1 days
10 M_{Earth}	6 hours
Earth	2 hours

Current options - Dedicated

OGLE

- Chile
- 1.4 deg^2,   1.3 m
- Excellent site

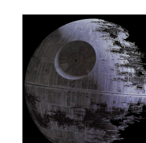


MOA

- New Zealand
- 2.2 deg^2,   1.8 m
- Bad weather/seeing

KMTNet

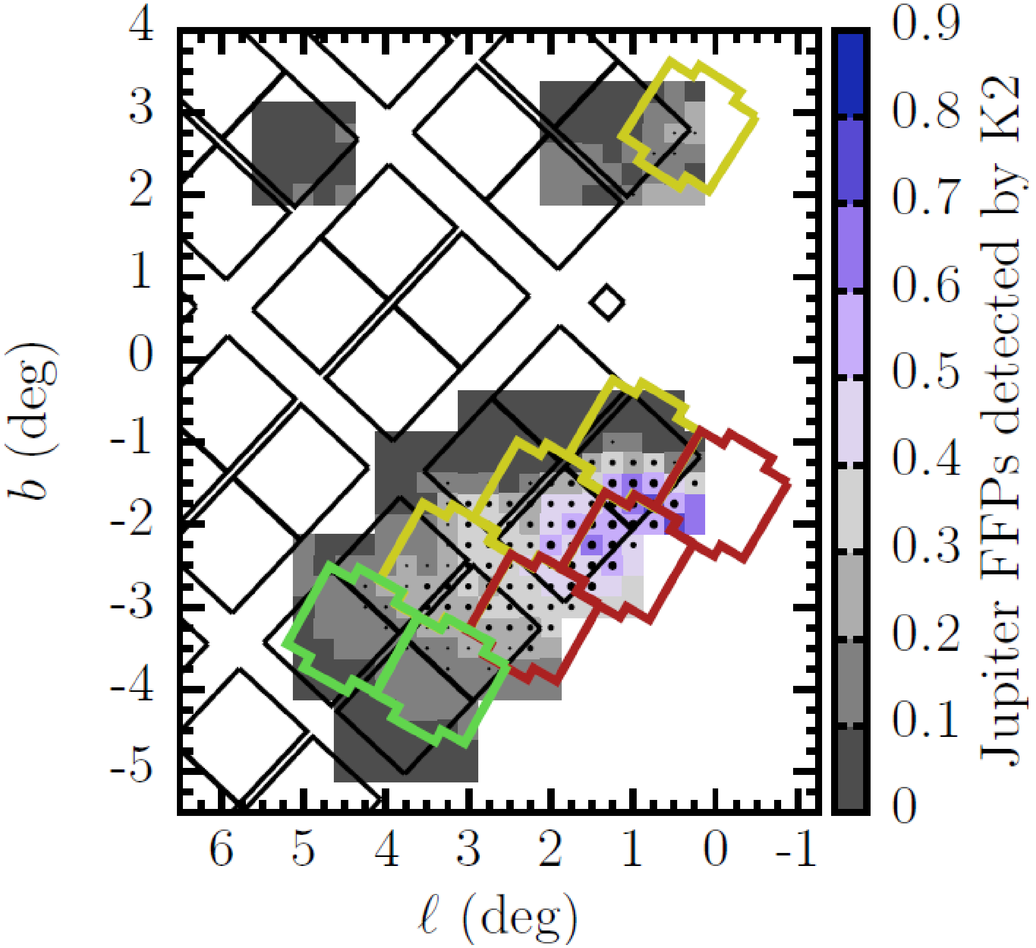
- Chile, S. Africa, NZ
- 4.0 deg^2,   1.6 m
- Not yet operational



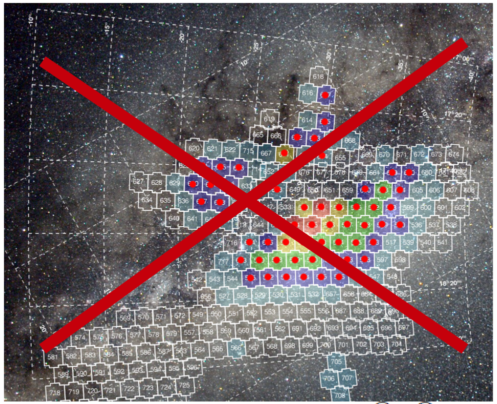
Can OGLE do it?
Not with the current strategy

- **Only a small patch of the K2 field is currently covered at high cadence**
- Tiling of K2 survey area is currently inefficient
- Color cadence:

  10s of days!



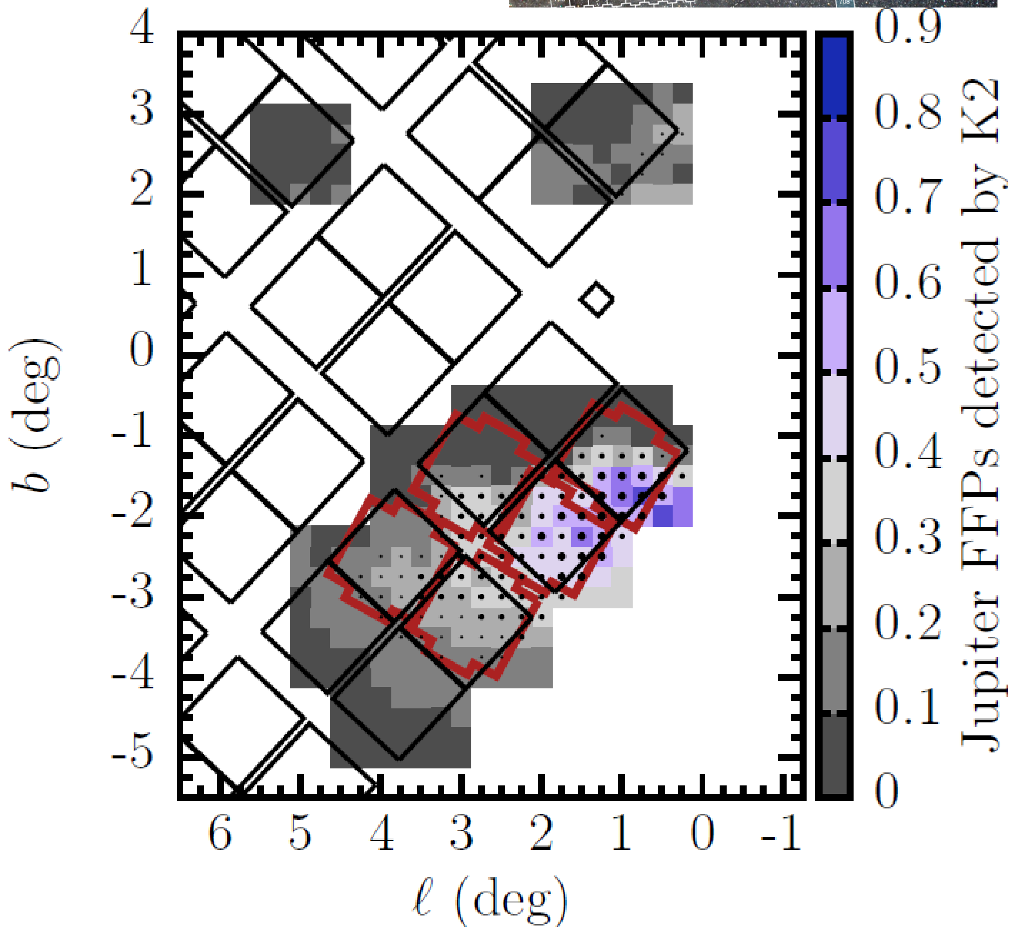
Can OGLE do it?
A radical strategy



Operations concept

- **Requires all but K2 fields abandoned**
- 5 fields at high cadence
- texp=100s *I*, 200s *V*
- 20s overheads
- 2 *I* exp, 1 *V* exp
- Color cadence:

  30-46 minutes

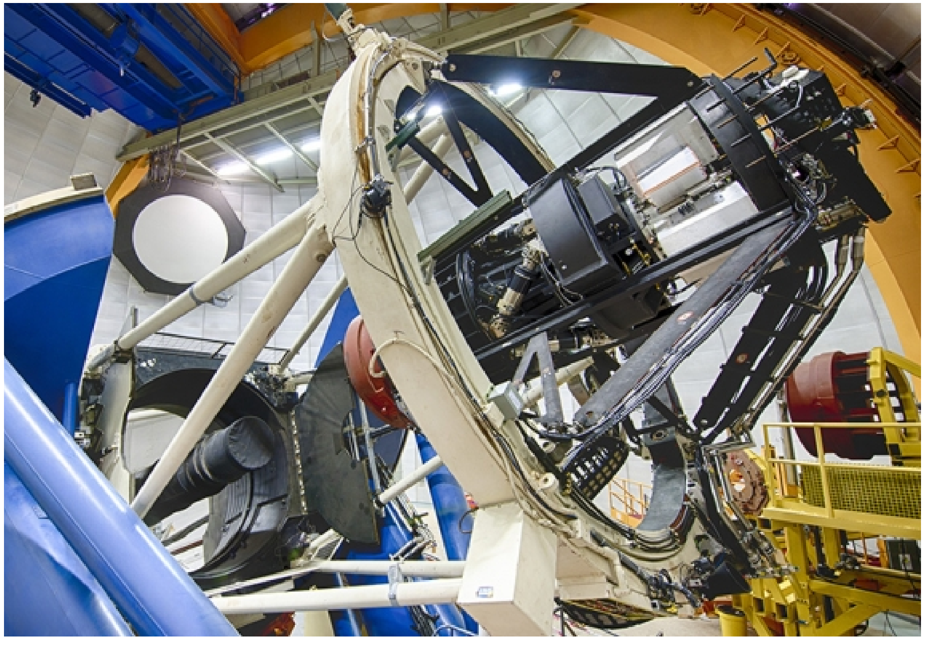


This might be enough...

Current options – Shared Time

DECam

- Chile
- 3 deg^2, 4 m
- Excellent site



VST @ Paranal

- 1 deg^2, 2.6 m

VISTA @ Paranal

- 1.65 deg^2, 4 m
- IR – mismatched with K2

Skymapper @ SSO

- 5.2 deg^2, 1.3 m

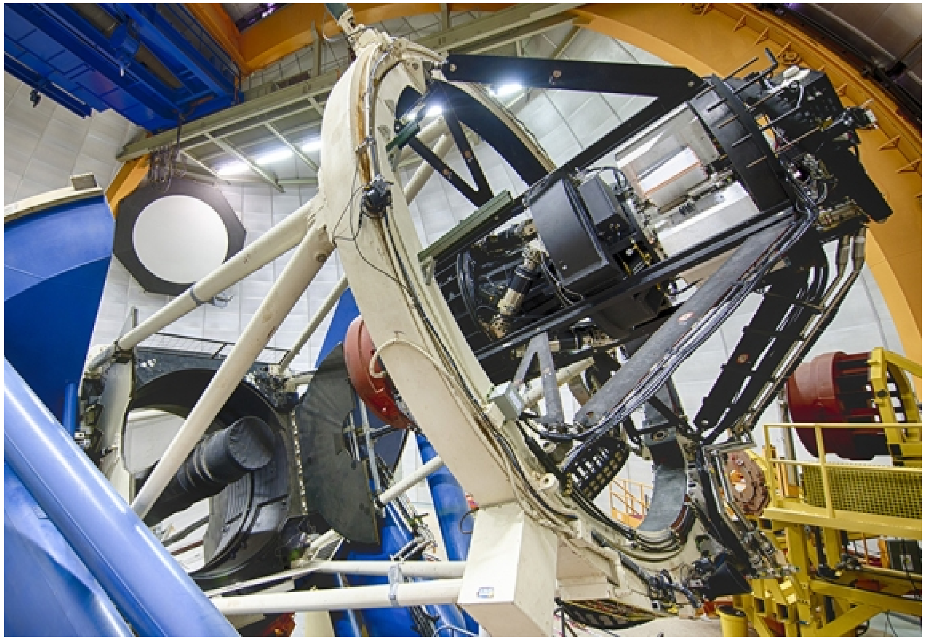
HyperSuprimeCam

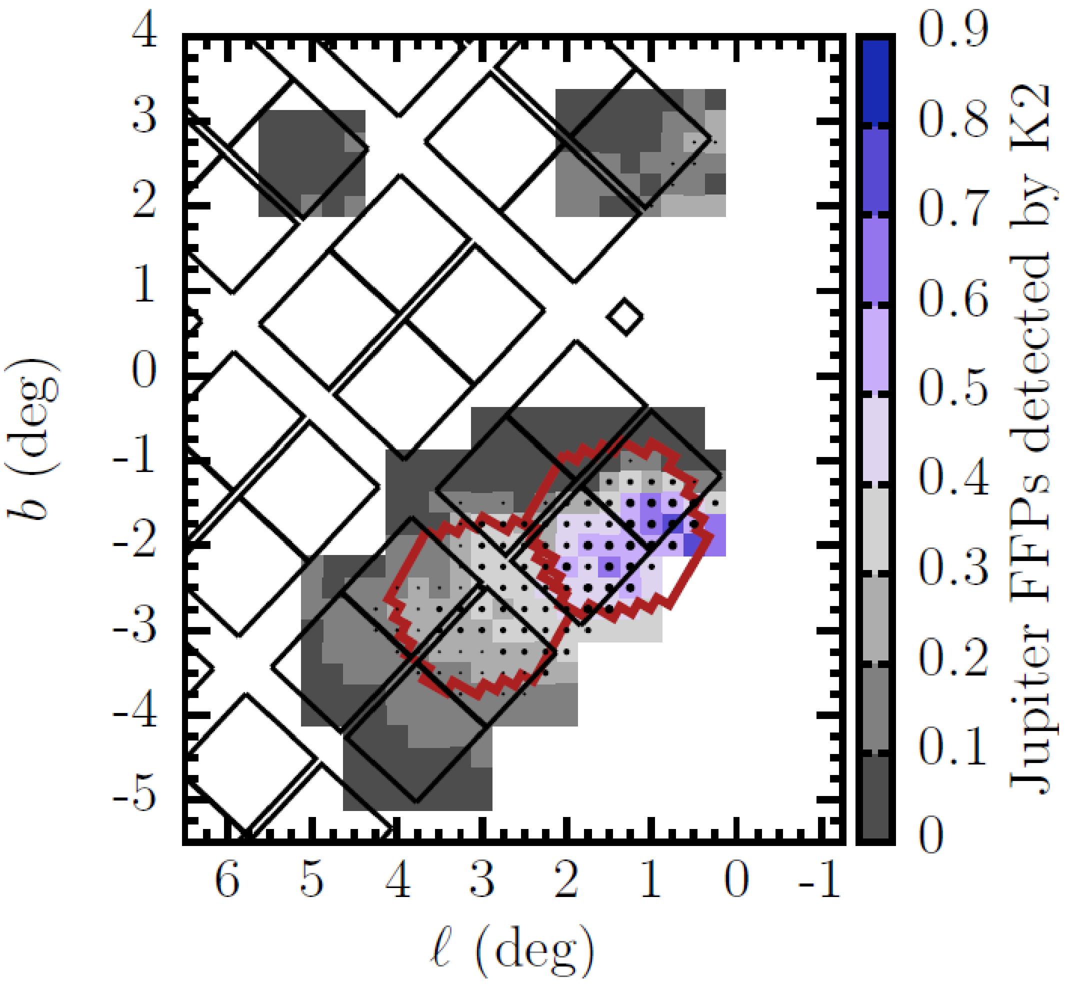
- 1.77 deg^2, 8 m
- Hawaii
- No fast filter changes

DECam for Microlensing

DECam vs OGLE

- ~10x Collecting Area
- >2x Field of View
- Same overheads



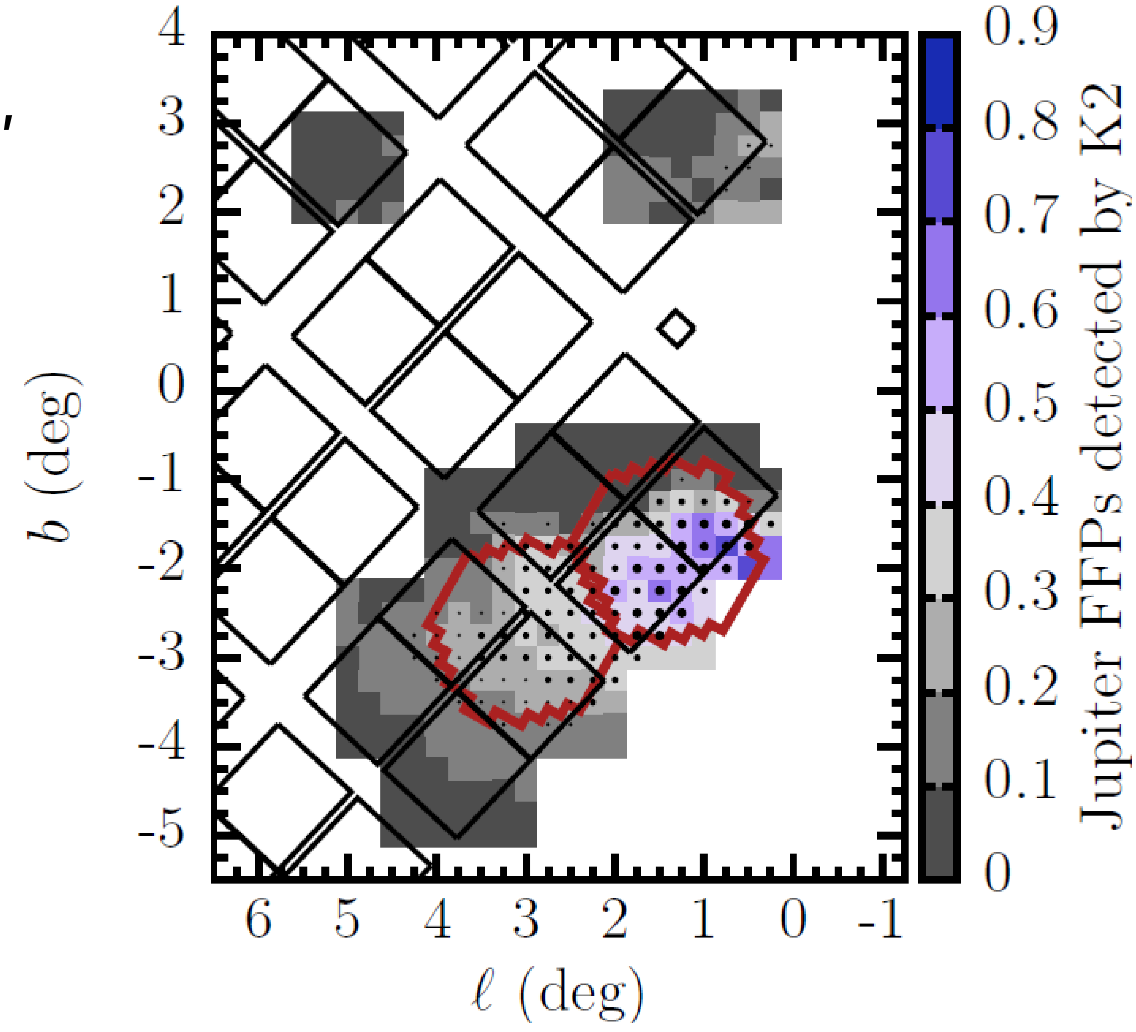


DECam Operations Concept

- Min 2 fields, up to 4
- texp=20s *z'*, 20s *r', 100s g'*
- 20s overheads
- Alternate z', r'
- Color cadence:

  r-z 2.5 minutes

  g   15 minutes
- Could replace r with wide VR filter

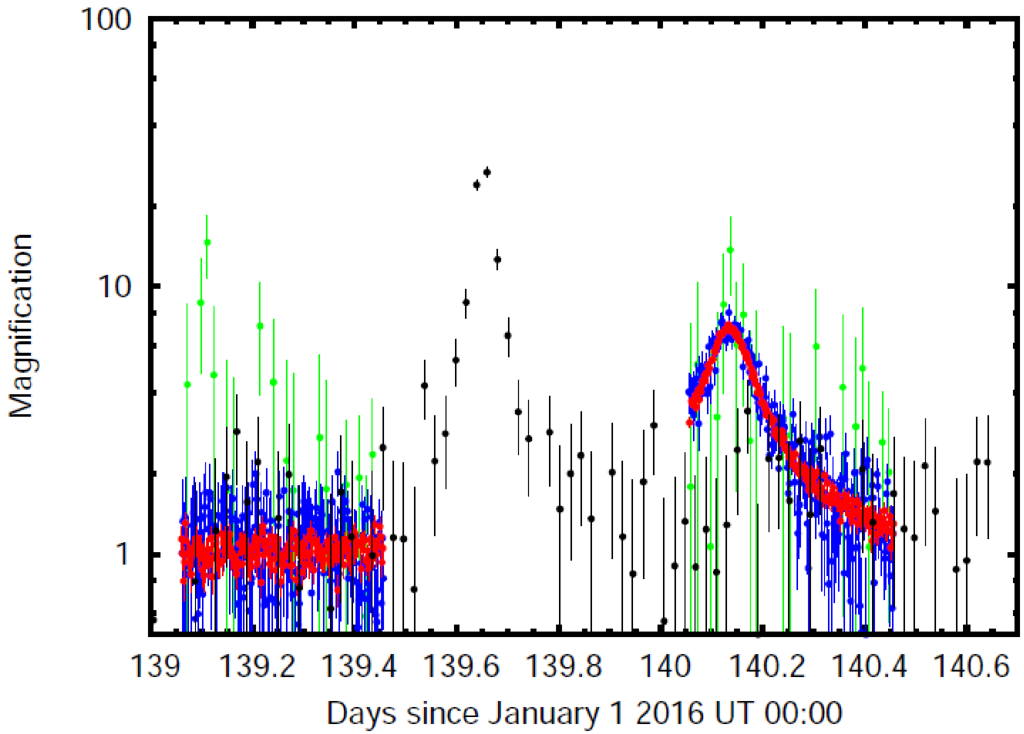


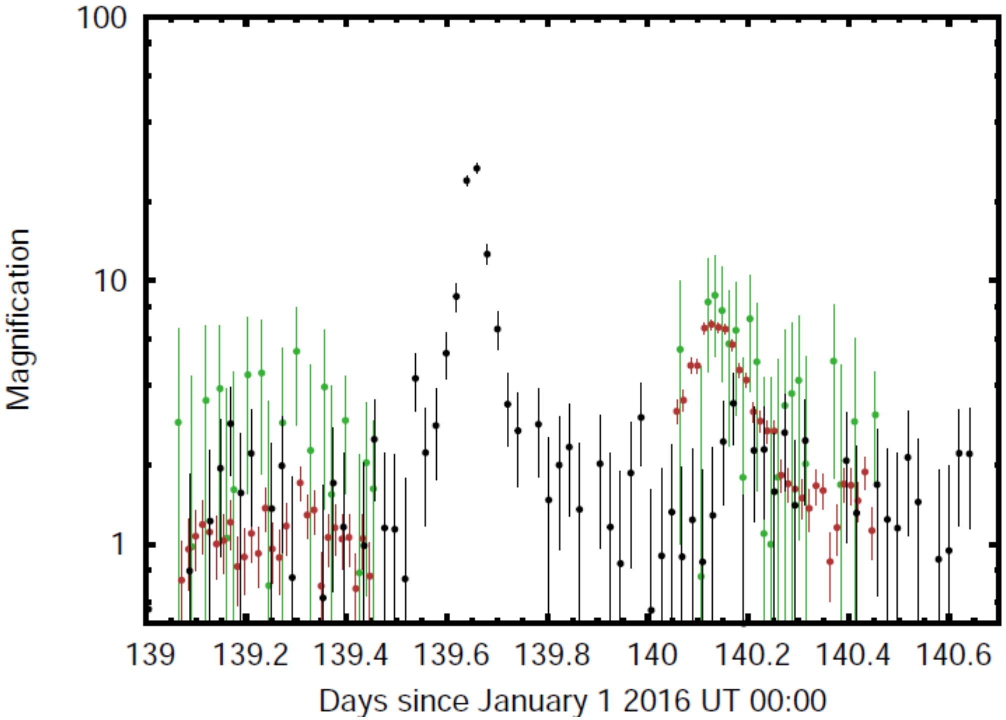
DECam – Public Data

- **Data will be made public on a timescale similar to the Kepler K2 date release** (raw images). Enabling:
  - The development of a larger US microlensing community
  - Deep KBO searches (gets colors + orbits)
  - Bolometric survey of large M-dwarf flares
  - Asteroseismology of bulge blue stragglers
  - Transiting planets (maybe, colors)
  - Color limb-darkening coefficients in binaries
  - What else can you think of...?

DECam vs OGLE (radical)

Saturn Mass (100 Earth) Free Floating Planet 6.9 Kpc away





Kp = 23.2 g' = 25.6 r' = 22.9 z' = 20.6

V = 24.1 I = 20.9

DECam errors:	
piE	4%
ThetaE (g-z)	1% (0.3 mag)
ThetaE (r-z)	2% (0.07 mag)

OGLE errors:	
piE	23%
ThetaE (V-I)	10% (0.45 mag)

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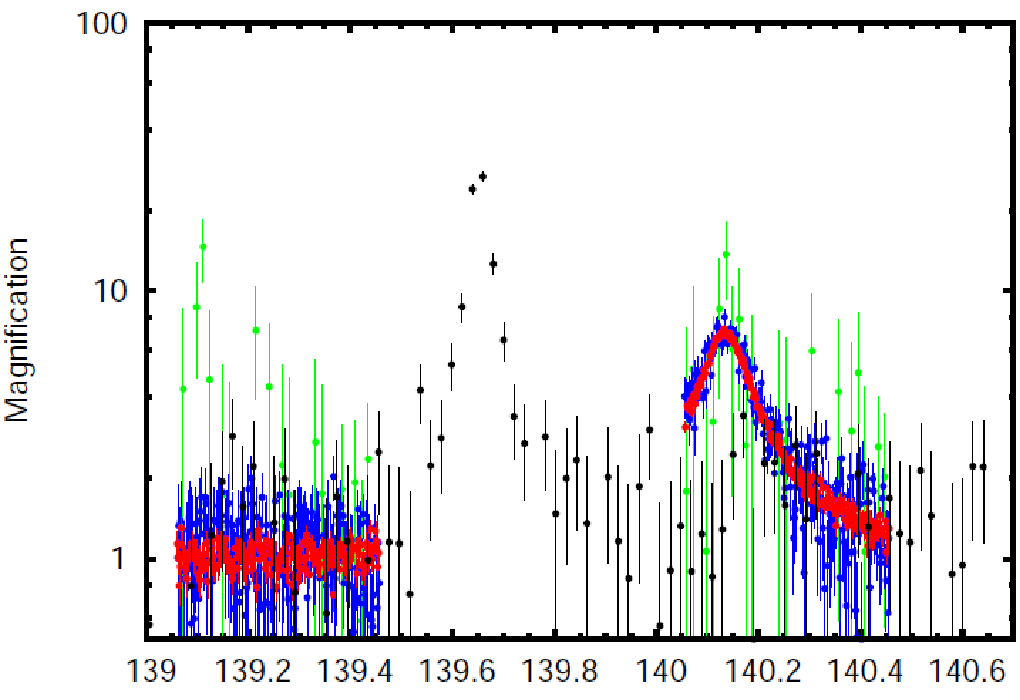

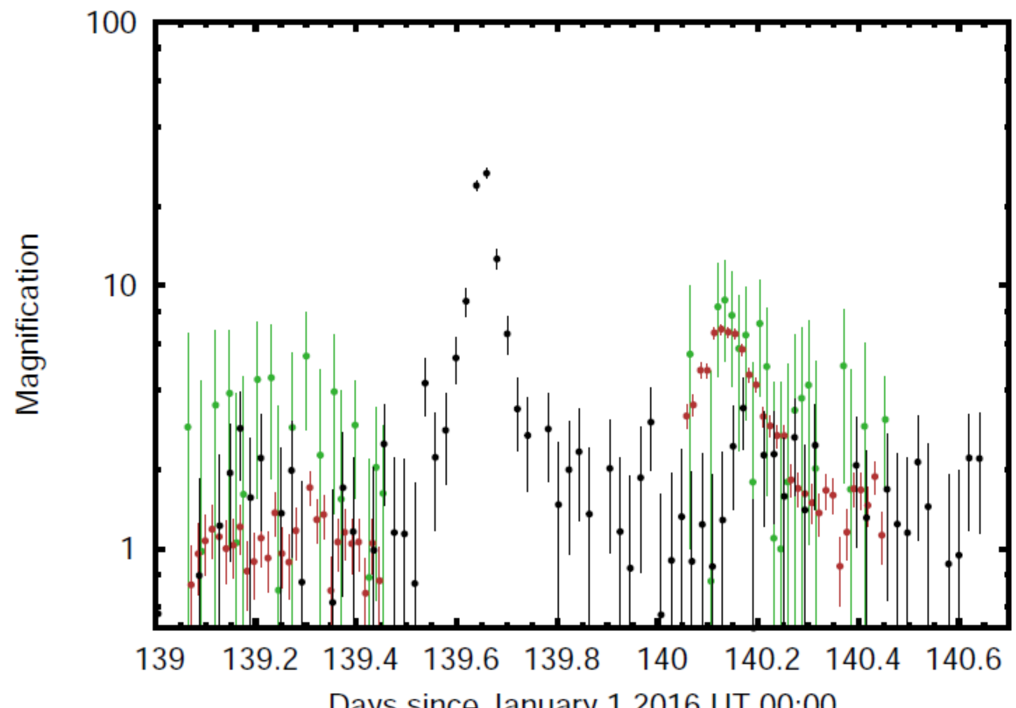

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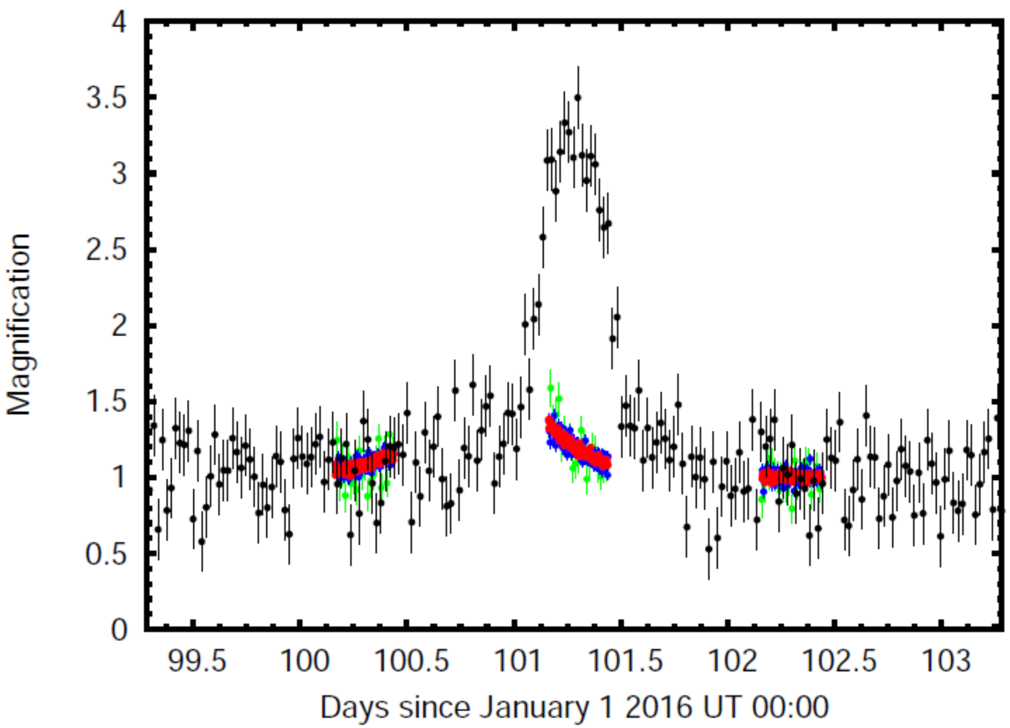
ThetaE (r-z)	2%	(0.07 mag)

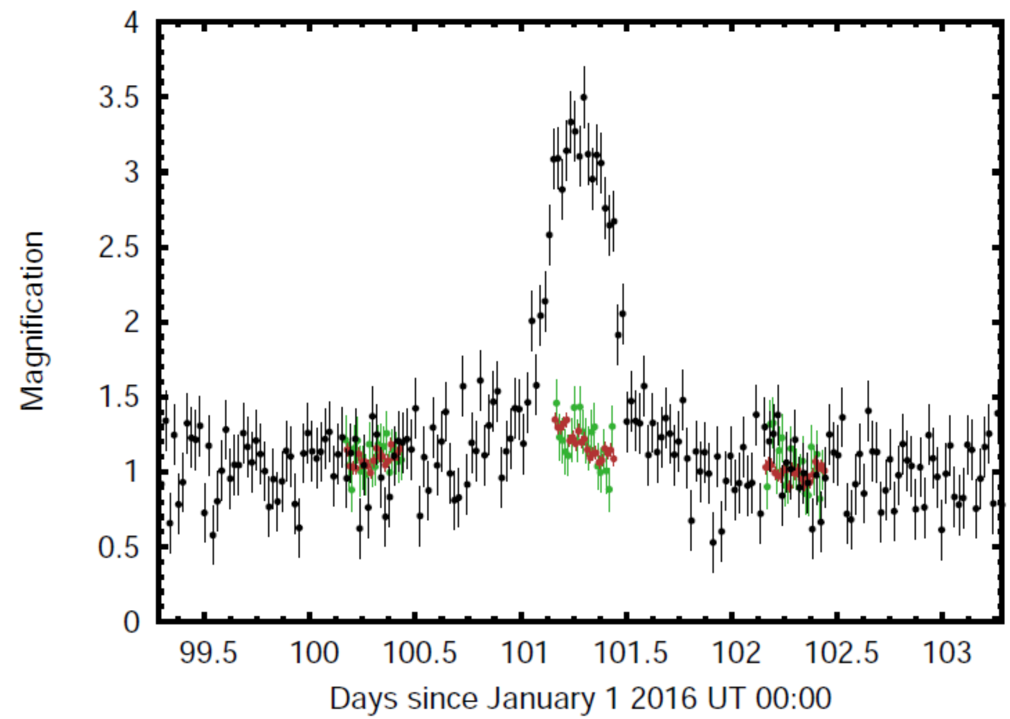
OGLE errors:

piE	23%	
ThetaE (V-I)	10%	(0.45 mag)

DECam vs OGLE (radical)

10 Earth-mass Free Floating Planet 8 Kpc away





Kp = 20.7 g' = 22.7 r' = 20.4 z' = 18.7

V = 20.4 I = 18.8

DECam errors:

piE	27%	
ThetaE (g-z)	14%	(0.53 mag)
ThetaE (r-z)	24%	(0.52 mag)

OGLE errors:

piE	75%	
ThetaE (V-I)	133%	(1.47 mag)

DECam vs OGLE (radical)

Number of Free Floating Planet Detections

- Assumes 5 sq degrees, 5.5 per star (3-3000M_{Earth}), $dN/dM \sim M^{-1.3}$ (Sumi+11 fit to MOA events)
- $\Delta X^2 > 500$ detection by Kepler
- Note that probably optimistic

Mass (M_E)	Detections K2	Mass K2+OGLE	Measurements K2+DECam
1000	3.5	~1.5	~3.1
300 Jupiter	6.5	~2.8	~4.1
100 Saturn	11.9	~3.0	~4.9
Total	22	~7	~12

DECam vs OGLE (radical)

DECam gives:

- 50% more mass measurements
- Factor of 4 (median) smaller error bars

than a completely overhauled OGLE survey

Mass (M_E)	Detections	Mass Measurements	
	K2	K2+OGLE	K2+DECam
1000	3.5	~1.5	~3.1
300 Jupiter	6.5	~2.8	~4.1
100 Saturn	11.9	~3.0	~4.9
Total	22	~7	~12

Conclusions

- K2 campaign 9, in combination with ground-based observations, will enable ***for the first (and maybe only) time*** definitive measurements of free-floating planet masses
- However, these mass measurements require high-cadence color measurements, which are difficult to achieve using the dedicated microlensing survey telescopes
- DECam on the Blanco is the best microlensing machine in the world – ***we must use it for this never to be repeated oppotunity***