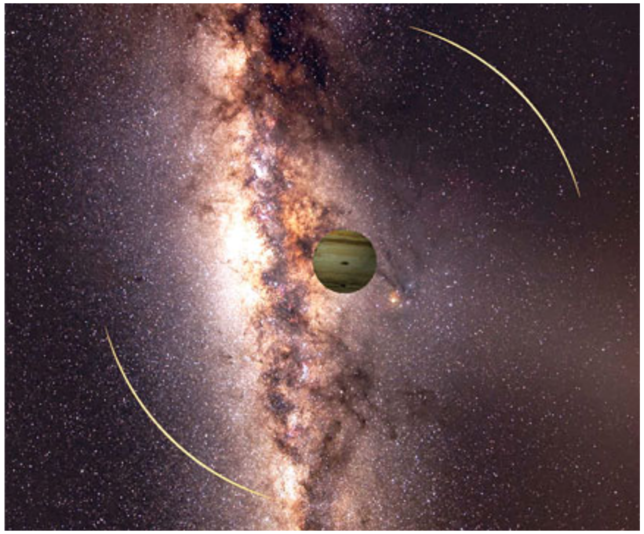
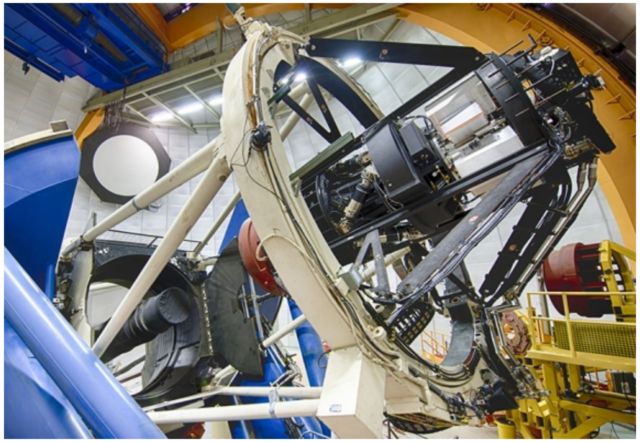
Measuring the Free-Floating Planet Mass Function with K2 & DECam





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Takeaway message

- K2's campaign 9 offers a unique opportunity to measure the masses of free-floating planets that is likely ***not to be repeated***
- Free-floating planet masses can only be measured if there is a ***simultaneous high-cadence 2+ color*** survey over the same area
- ***The only instrument that can do this and measure a sample of free-floating planet masses is DECam***

Outline

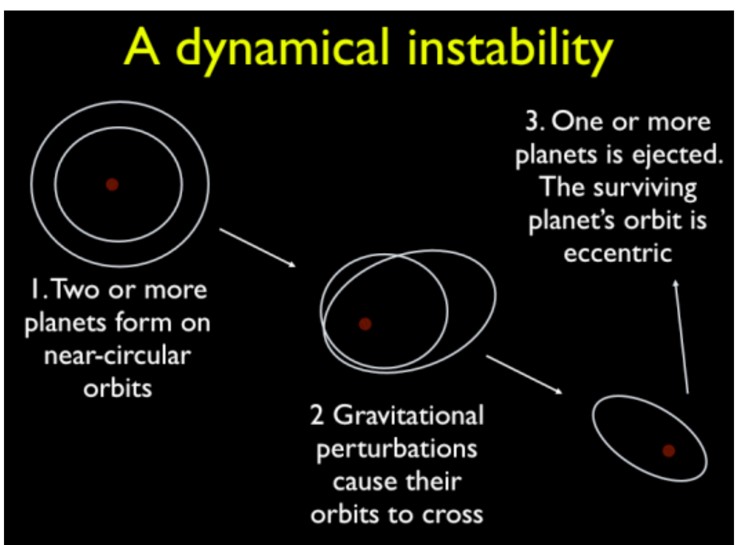
- How to detect free-floating planets and measure their masses
- K2 Campaign 9
- Why we need DECam

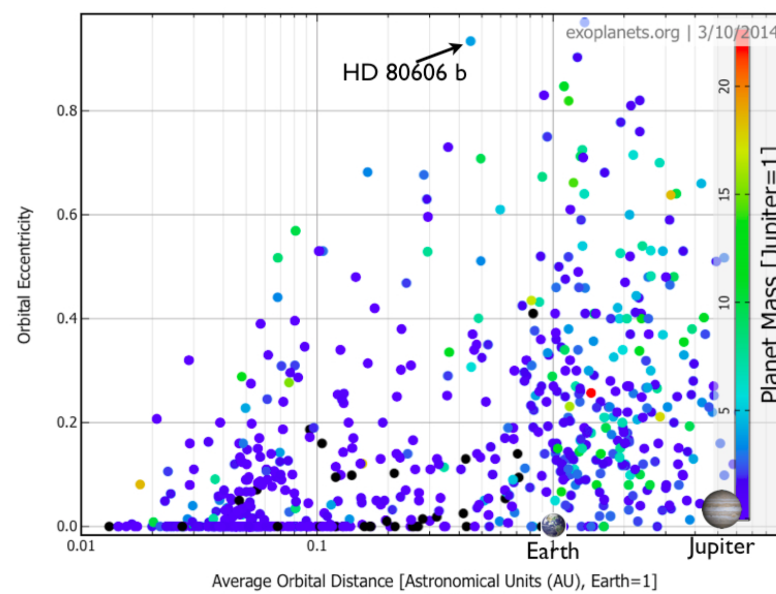
Free-Floating Planets

- Planets without host stars
- Probably form in low numbers as failed stars

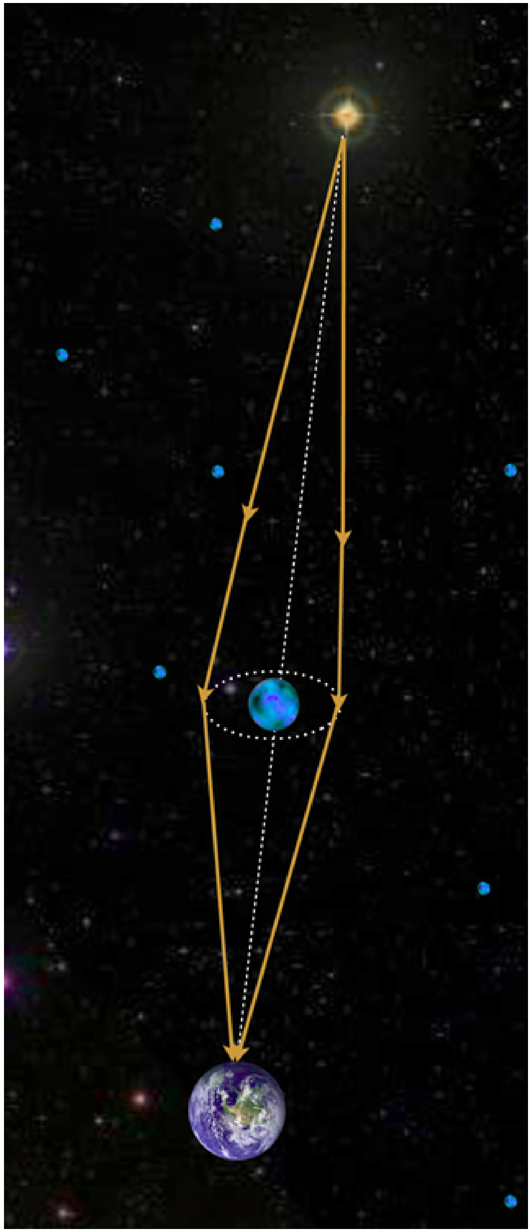
Free-Floating Planets

- Planets without host stars
- Probably form in low numbers as failed stars
- More probably formed through ejections of planets after protoplanetary disk dissipation





Microlensing Events



Source

Lens – the free-floating planet

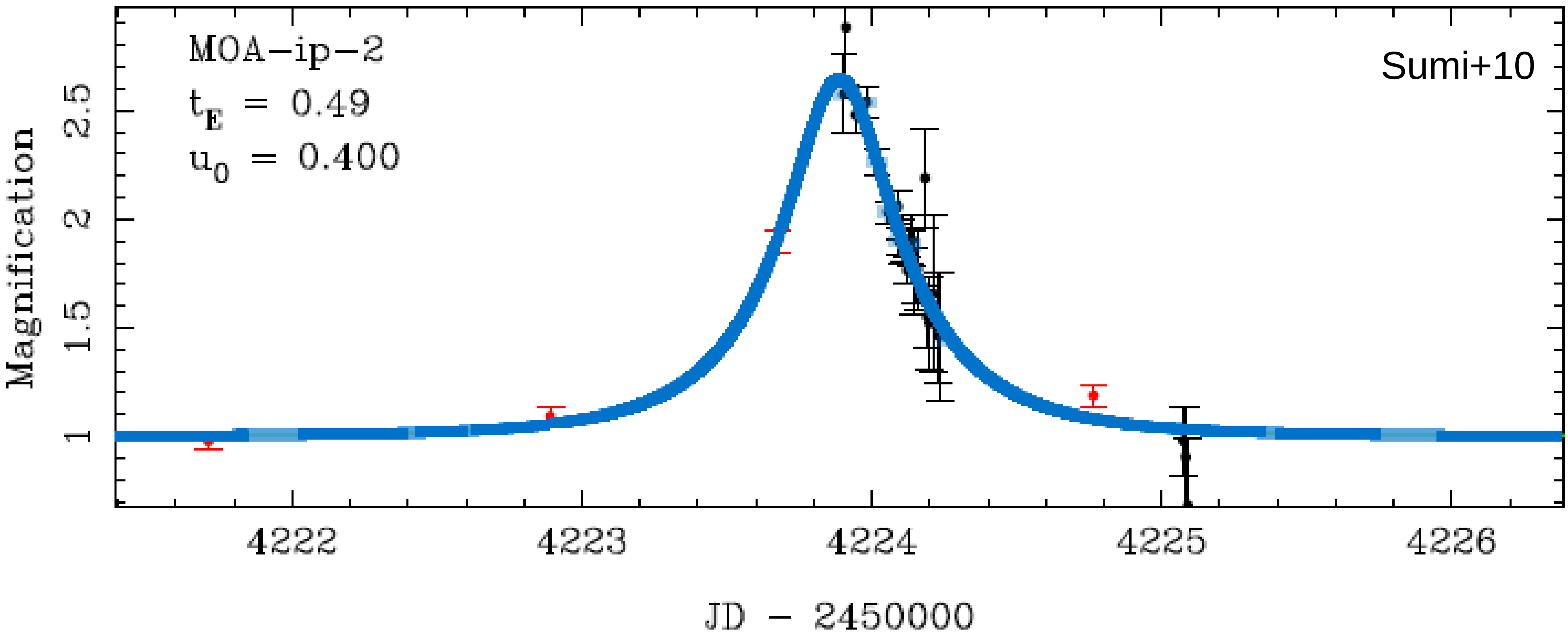
Observer

Microlensing Events

There is one physical observable

Timescale = Einstein Radius / Rel. Proper Motion

$t_E \quad = \quad \theta_E \quad / \quad \mu_{geo}$



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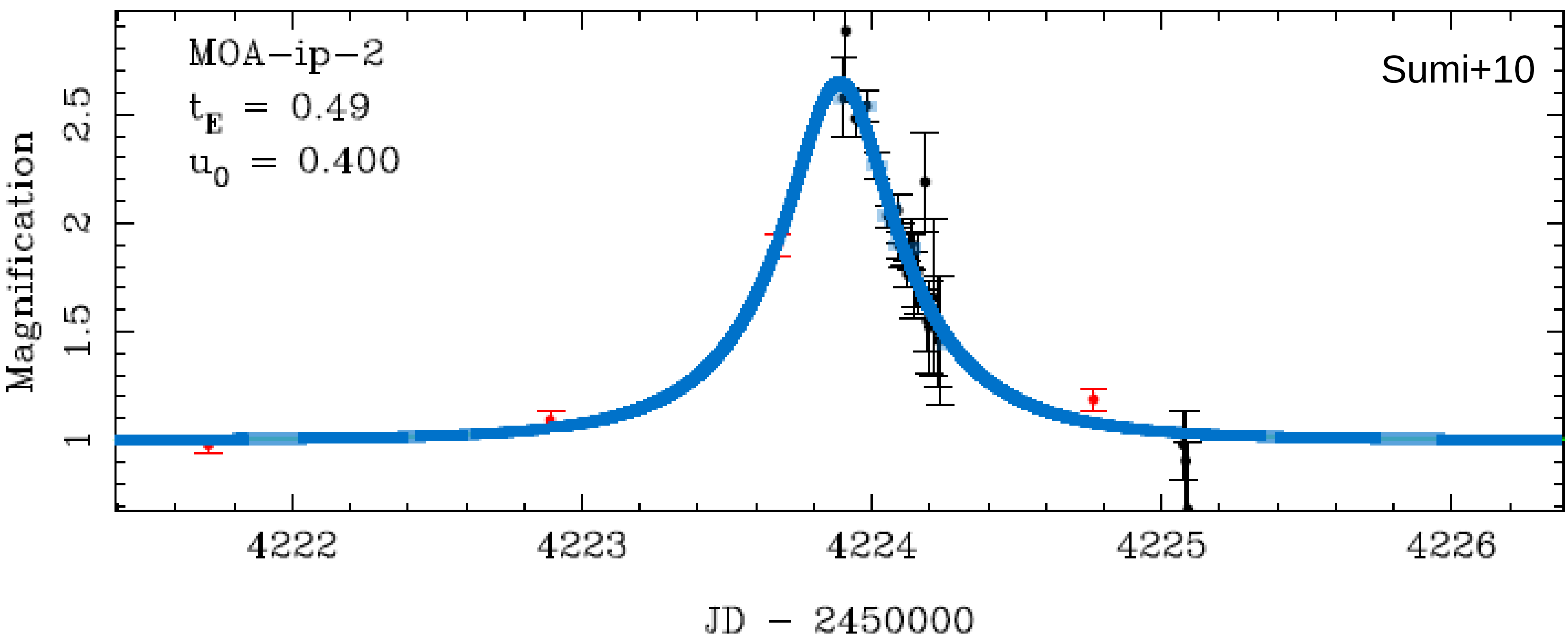


Microlensing Events

Timescale is a function of

- Lens mass
- Lens and source distances
- Lens-source relative proper motion

$\left.\begin{array}{l}\text{Lens mass}\\ \text{Lens and source distances}\end{array}\right\}$ Einstein radius

$$t_{\mathrm{E}} = \frac{\theta_{\mathrm{E}}}{\mu_{\mathrm{geo}}}$$

$$\theta_{\mathrm{E}}^2 = \kappa M \pi_{\mathrm{rel}}$$

$$\kappa \equiv \frac{4G}{c^2\,\mathrm{AU}} \simeq 8.1\,\frac{\mathrm{mas}}{M_{\odot}}$$

Microlensing Events

Typical proper motion ~ 5 mas / yr

Typical relative parallax ~ 1/24 mas

Typical timescales

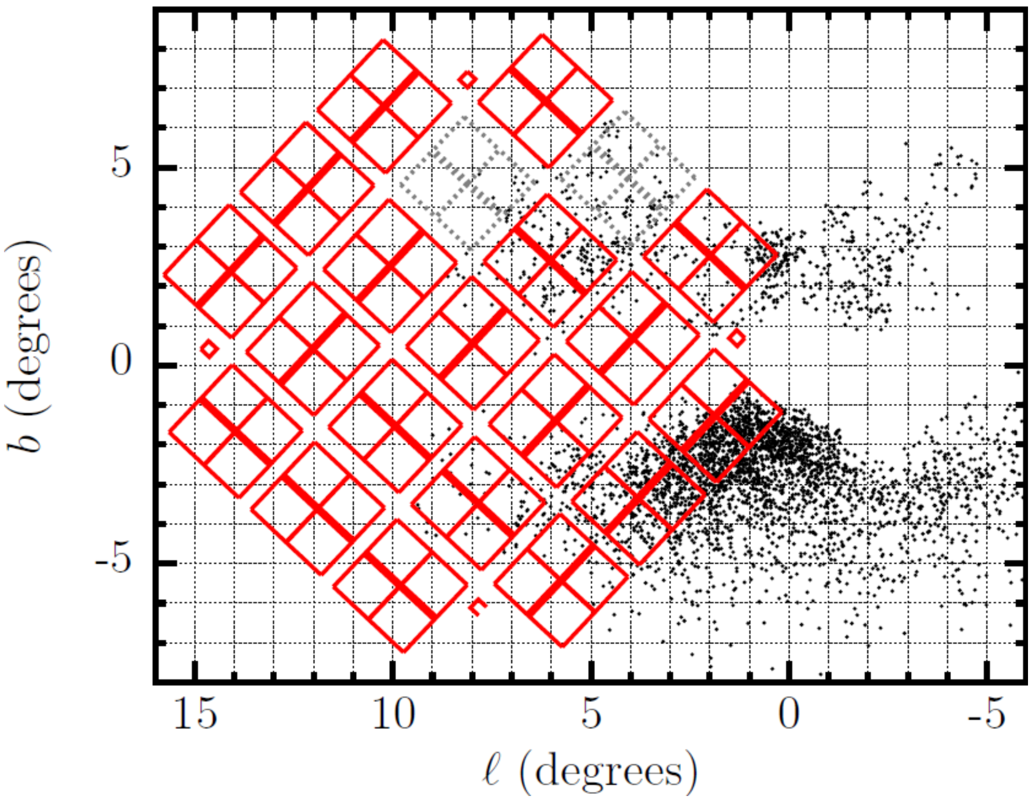
1 Msun	40 days
0.3 Msun	20 days
Jupiter	1 days
10 M_{earth}	6 hours
Earth	2 hours

Finding Free-Floating Planets

- Must match cadence to timescale
  - Aim for >3 points per timescale
- Additionally, rate scales as $\sqrt{M}$
  - Lower masses require more sky coverage and/or deeper exposures

K2 Campaign – more later

- ~ 80 days (0.22 years)
- Up to ~6 sq. degrees
- Much deeper exposures and continuous coverage, but extreme blending – overall a win



K2 Campaign – more later

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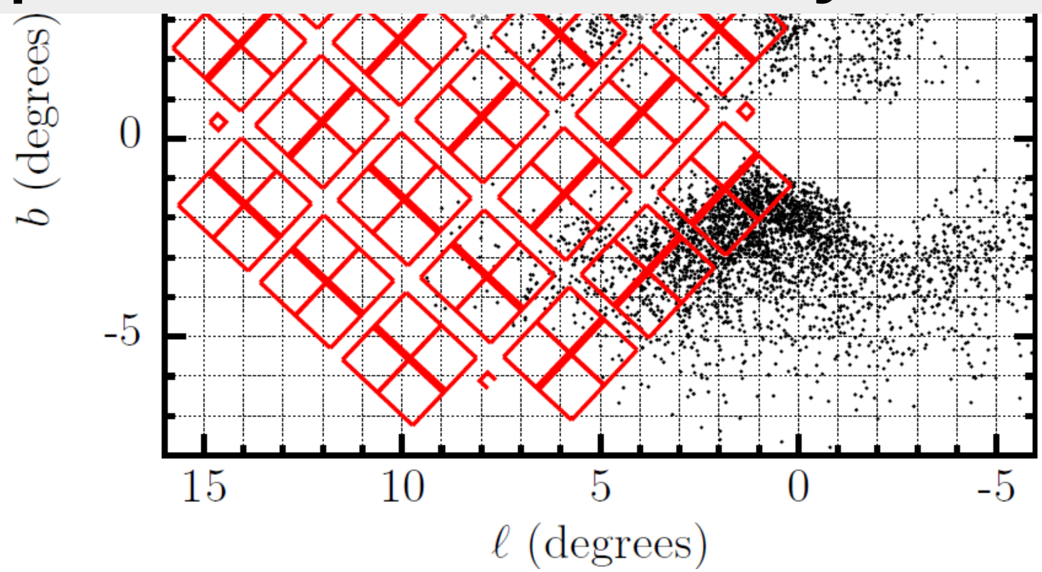
Expect ~10s of free-floating planet detections by K2



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We need more physical observables

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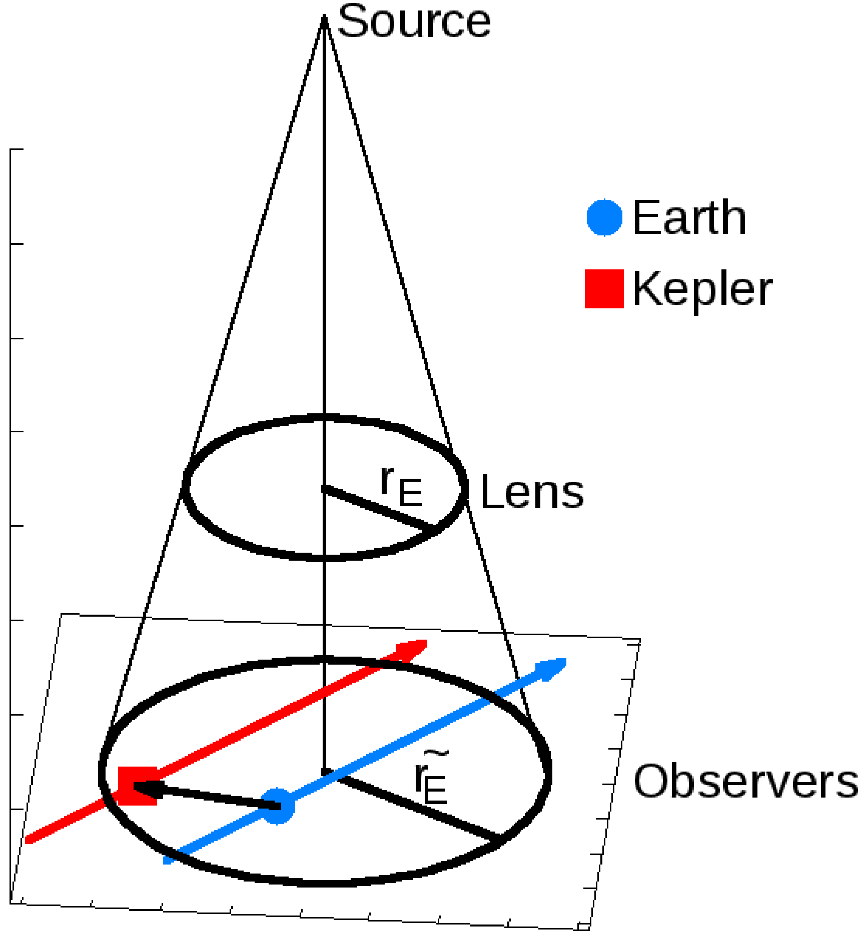
We need more physical observables

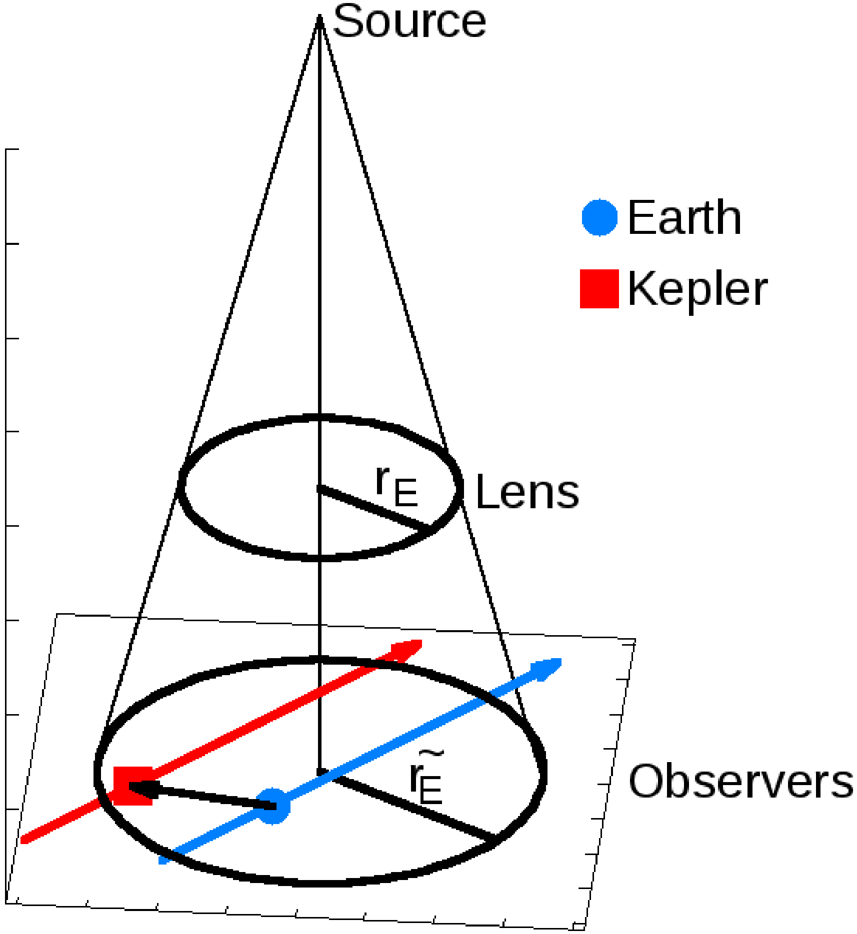
I. Parallax
II. Finite Source Effects

Parallax



- Microlensing requires precise alignment
- Change observer position and you change the event
- Observe from 2 positions and you have a ruler to measure a projection of the Einstein radius

Parallax



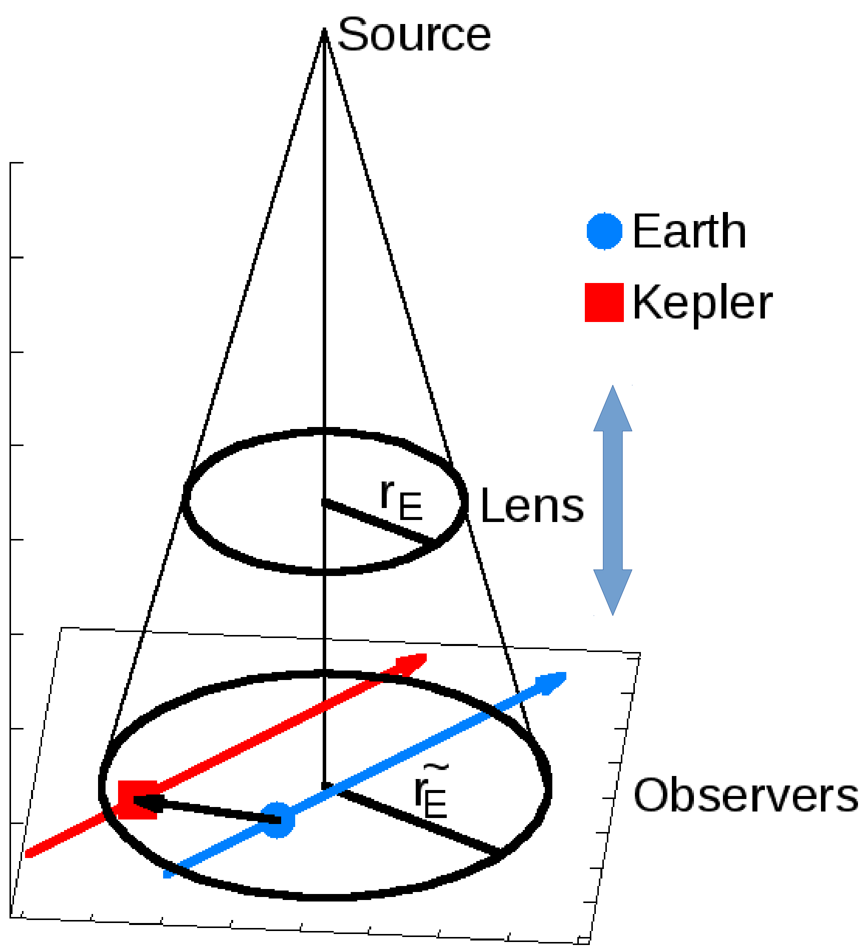
What does it get you?

Let's define $\pi_E \equiv \dfrac{\mathrm{AU}}{\tilde{r}_E}$

Sub. In definitions to get

$$\pi_E = \sqrt{\frac{\pi_{rel}}{\kappa M}}$$

Parallax



$$\pi_E = \sqrt{\frac{\pi_{rel}}{\kappa M}}$$

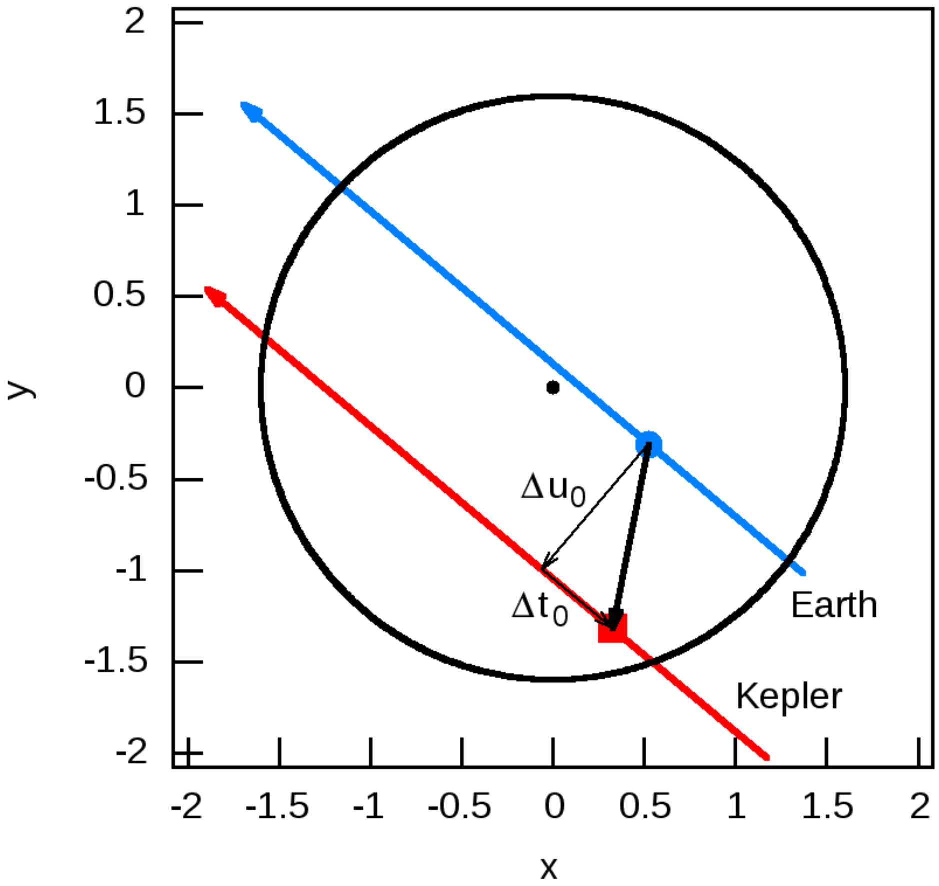
One observable, two unknowns

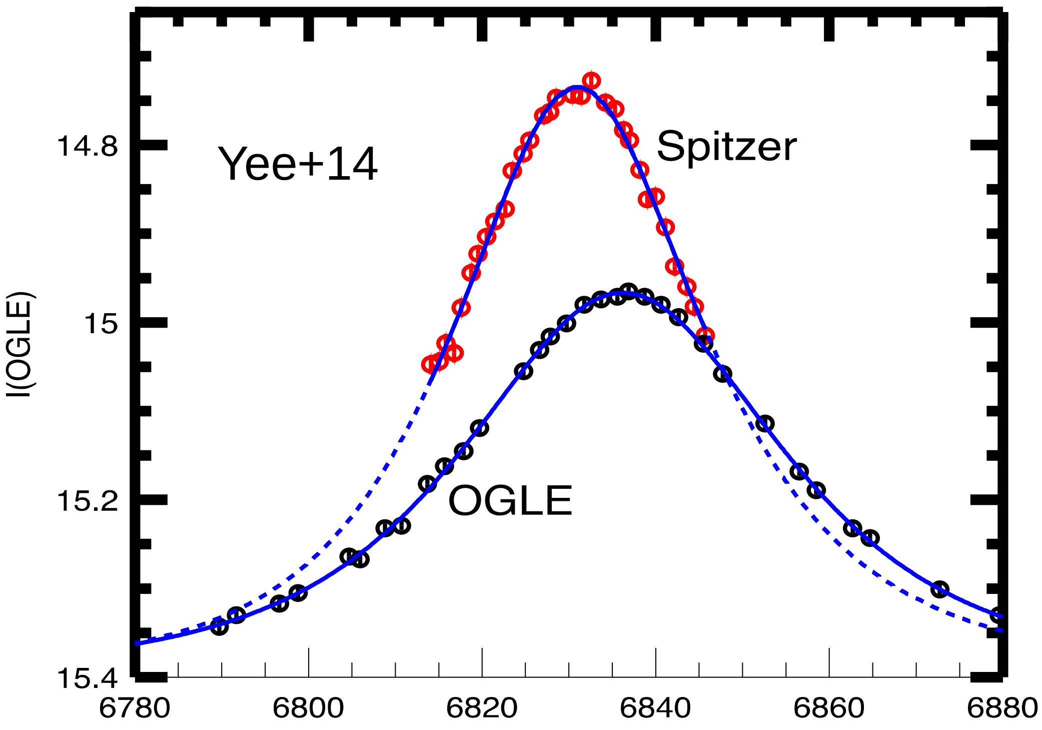
Mass as a function of relative parallax

But recall:

$$\theta_E^2 = \kappa M \pi_{rel}$$

Parallax is a 2D effect





Getting to Two Observables Two Unknowns

Parallax gives us:

$$\frac{M}{\pi_{\rm rel}} = \frac{1}{\kappa \pi_{\rm E}^2}$$

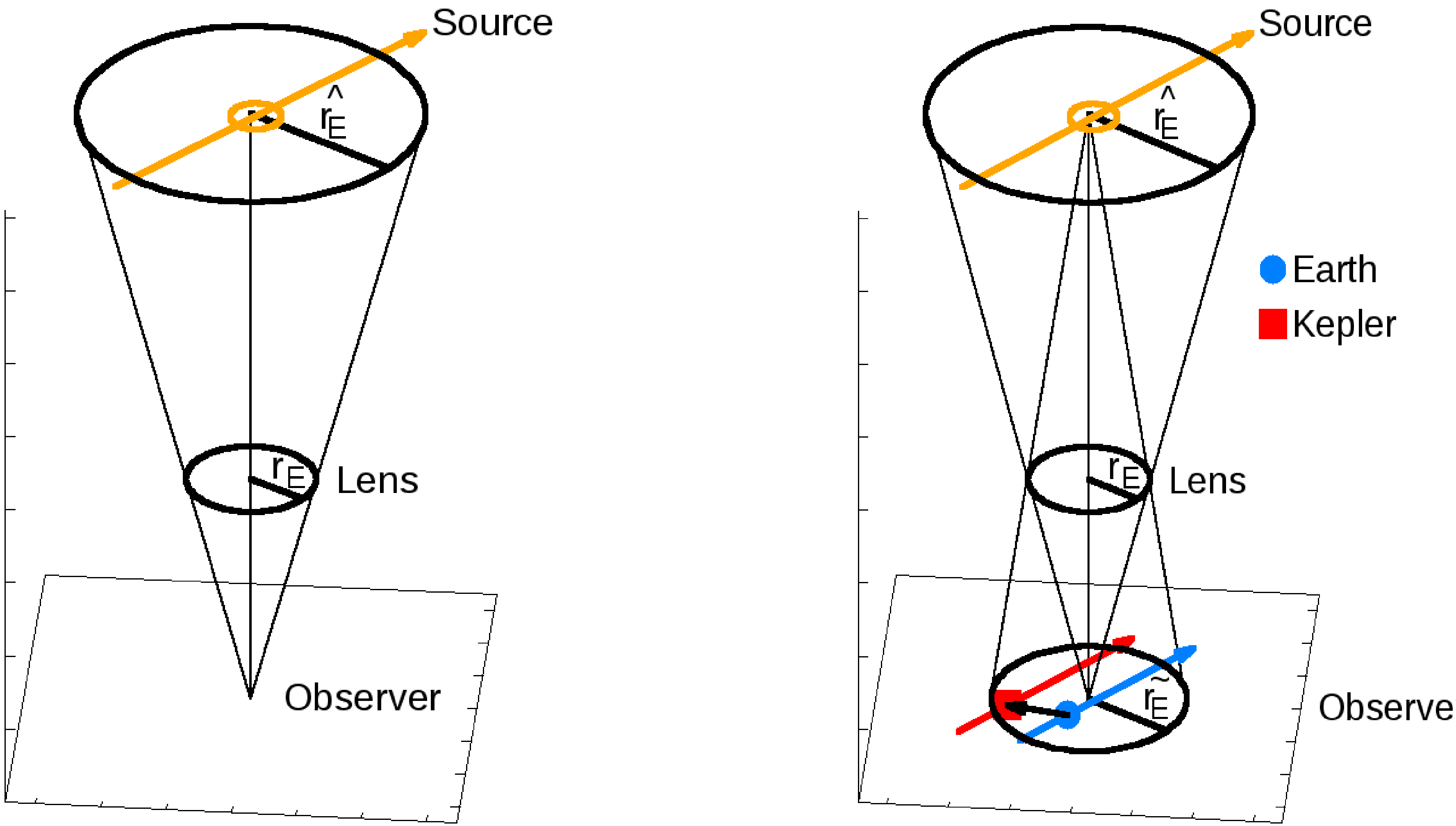
What gives us θ_E?

$$M\pi_{\rm rel} = \frac{\theta_{\rm E}^2}{\kappa}$$

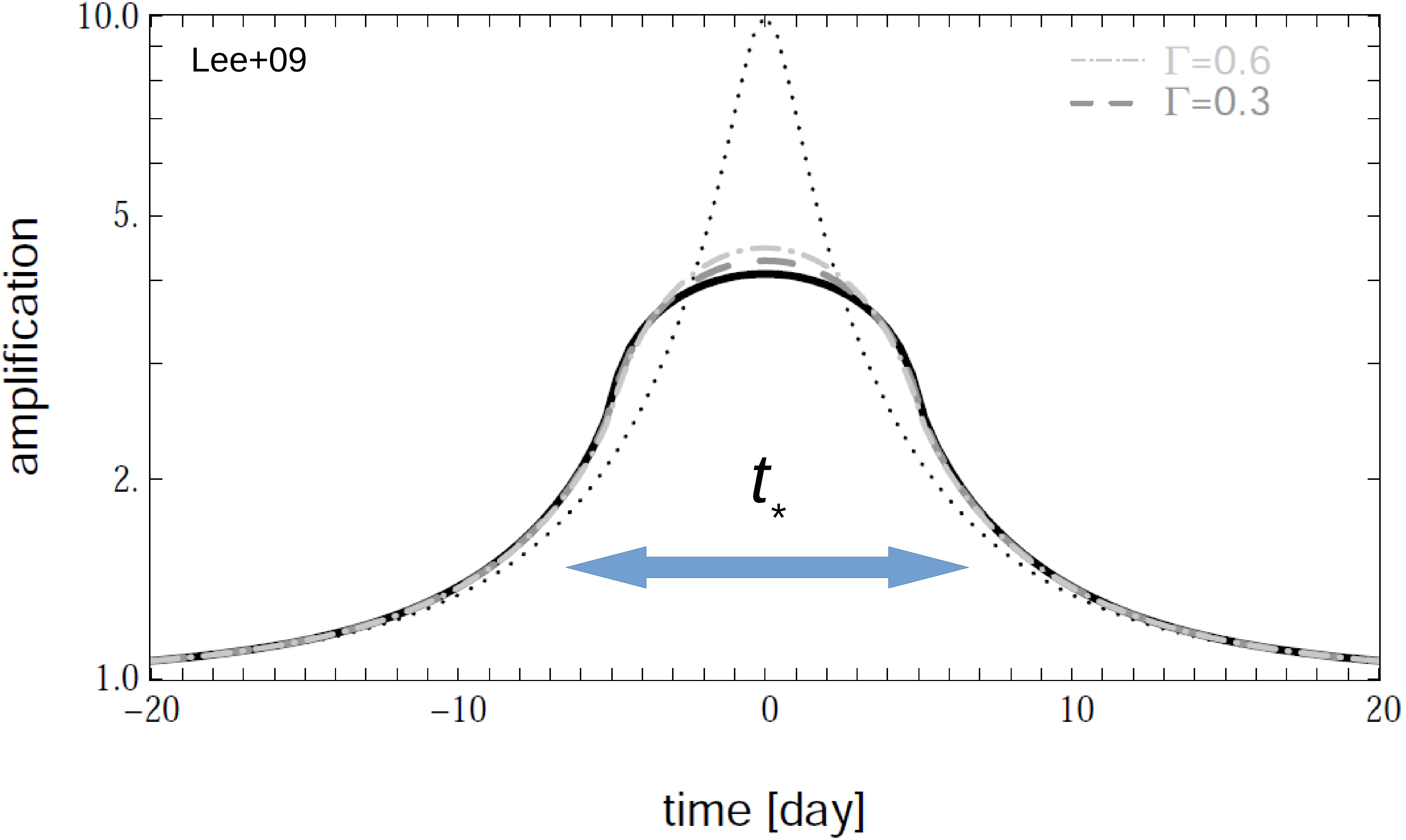
$$M = \frac{\theta_{\rm E}\pi_{\rm E}}{\kappa}$$

$$\pi_{\rm rel} = \frac{\theta_{\rm E}}{\pi_{\rm E}}$$

Parallax & Angular Einstien Radius



Finite Source Effects



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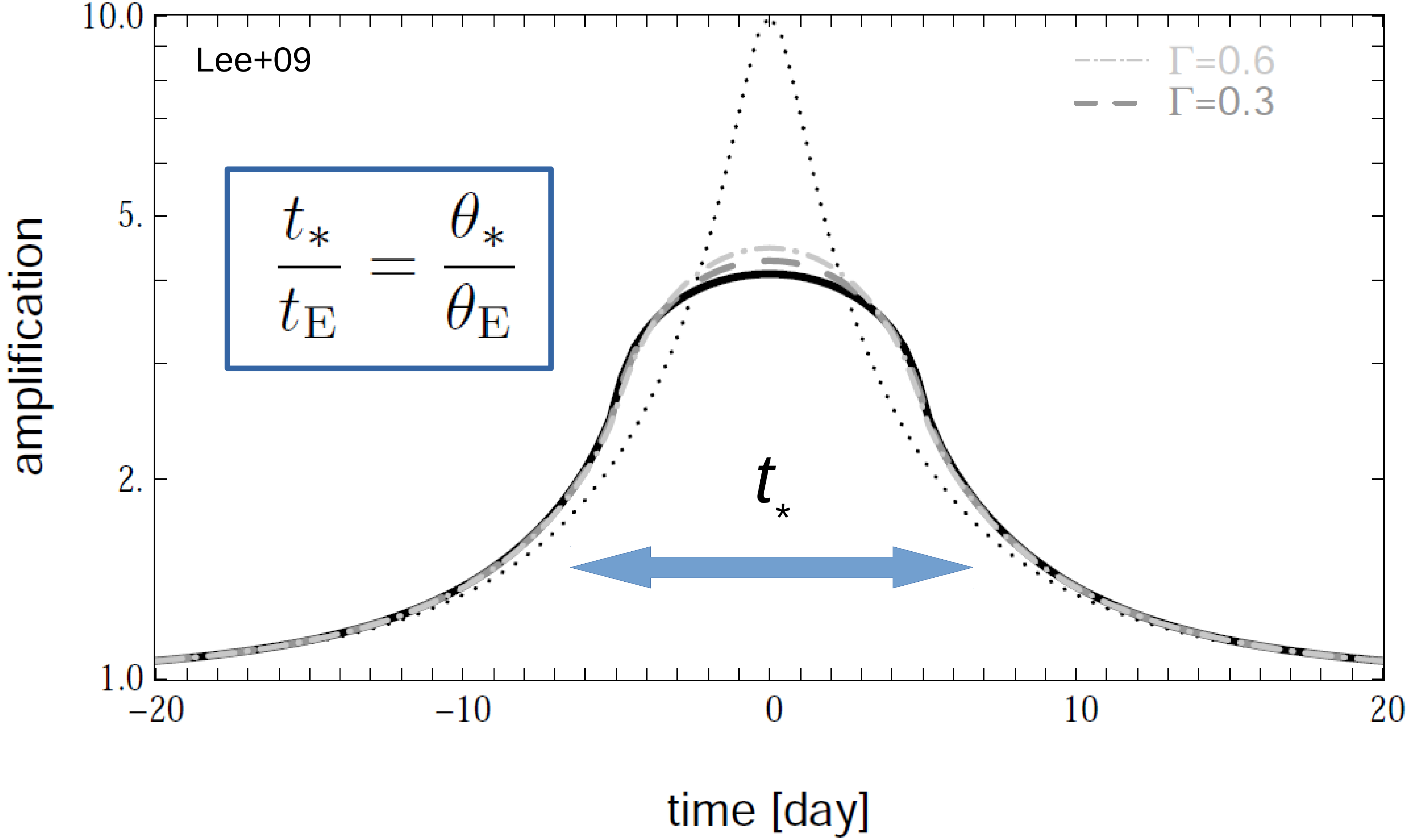


Finite Source Effects

Known

Angular Diameter
Knowable

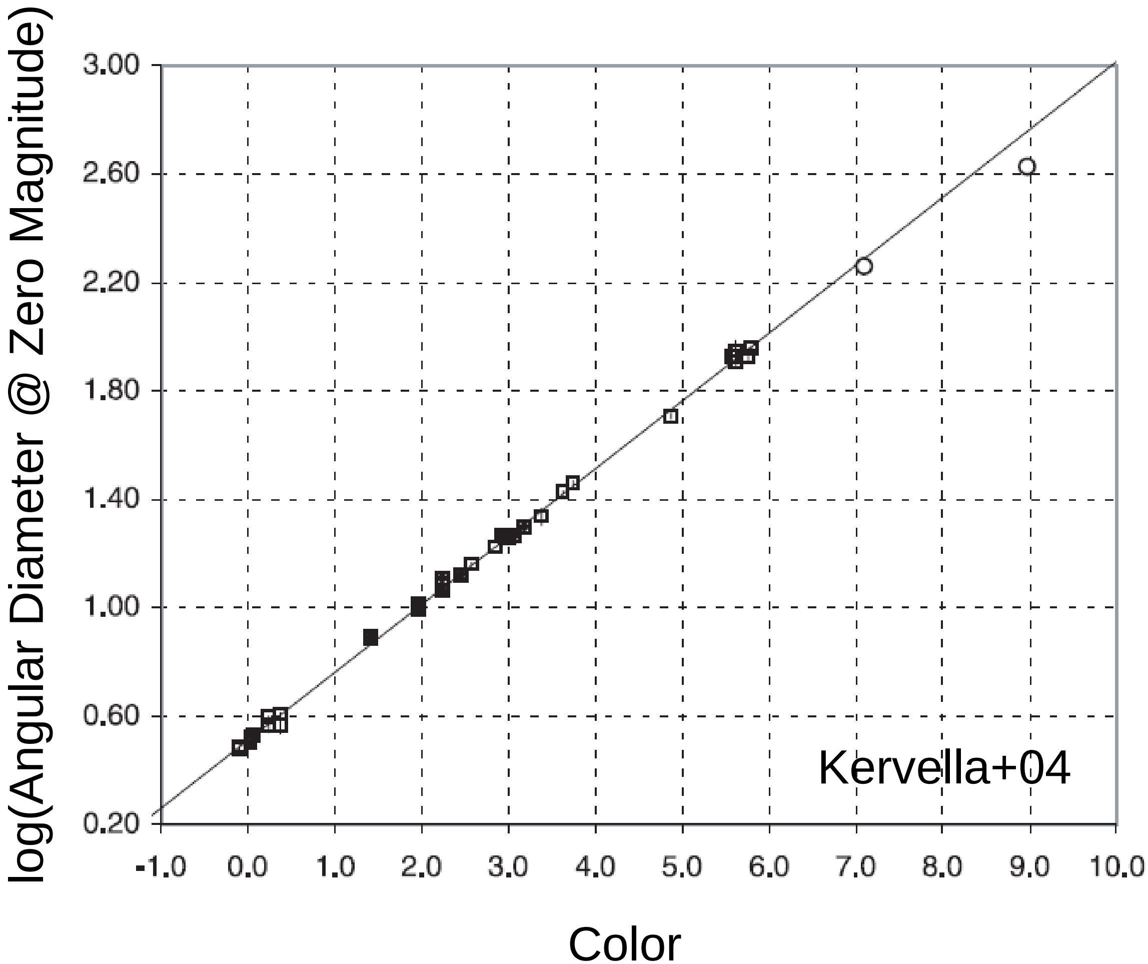
$$\frac{t_*}{t_\mathrm{E}} = \frac{\theta_*}{\theta_\mathrm{E}}$$

Known

Unknown

Surface Brightness-Color Relations

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



e.g.

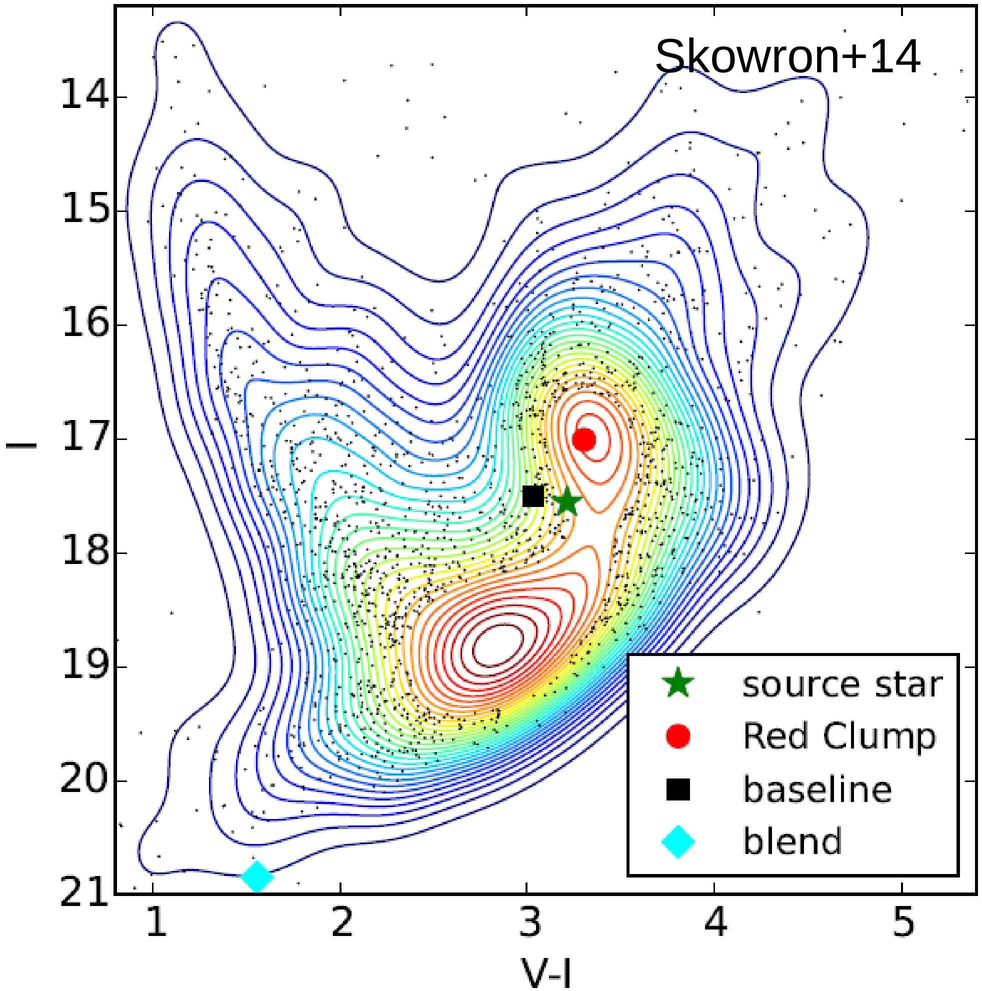
$\log \theta_{LD}$

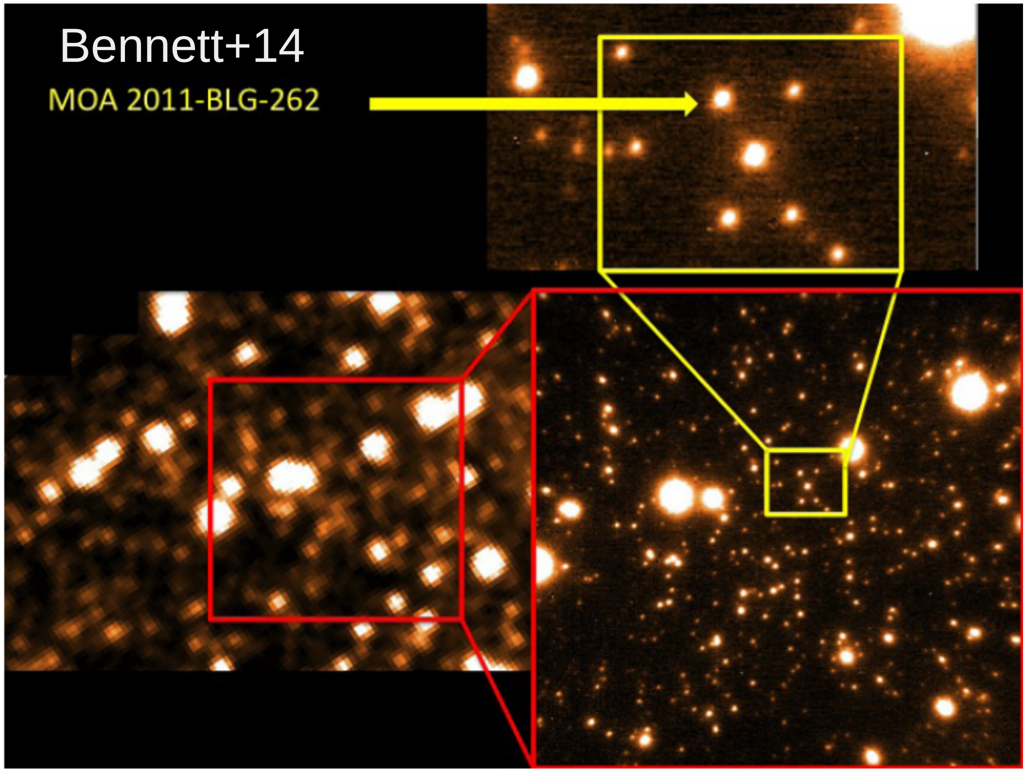
$= 0.0755\ (V\text{-}K) + 0.5170 - 0.2\ K$

Other relations for other colors

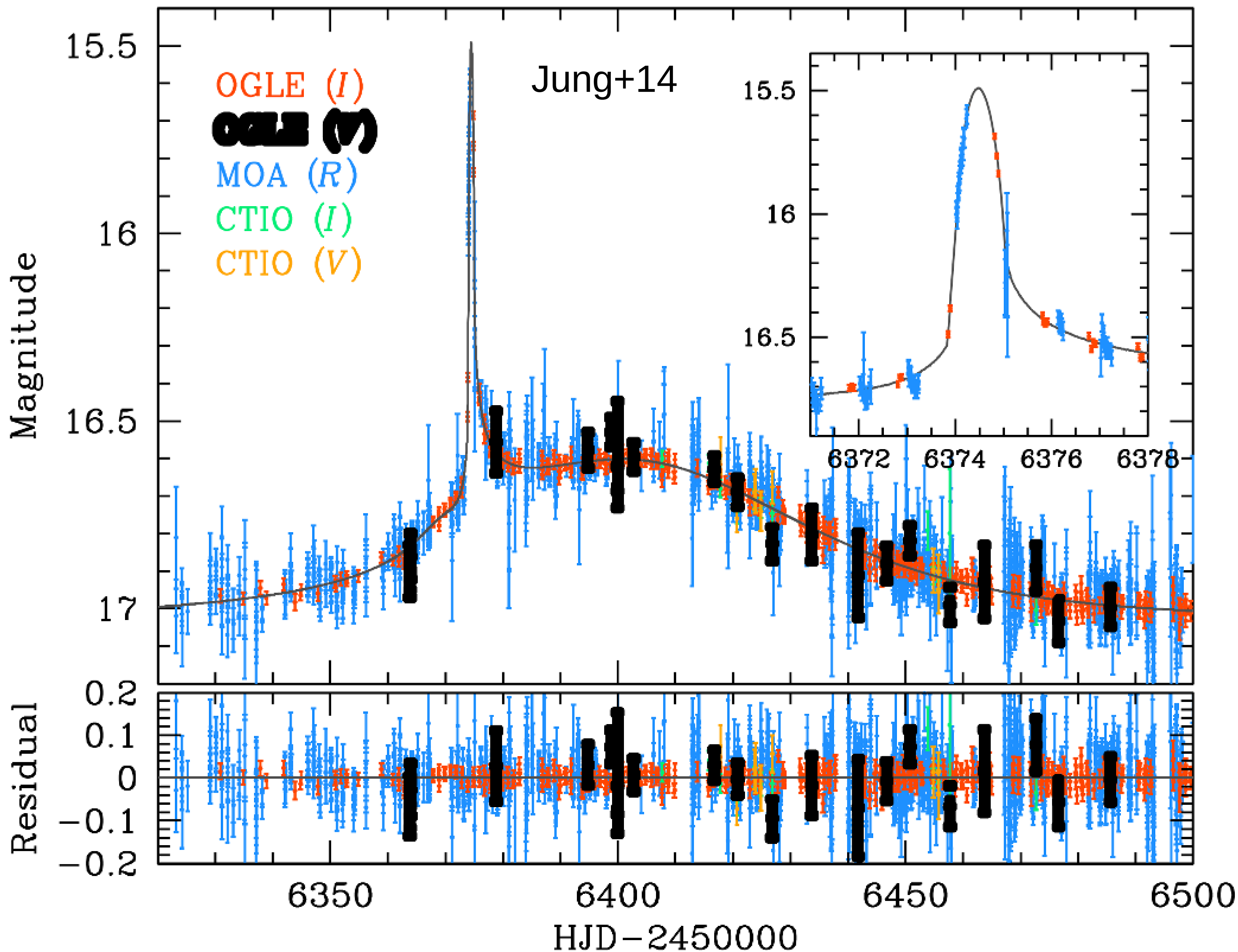
But you must isolate the source

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?

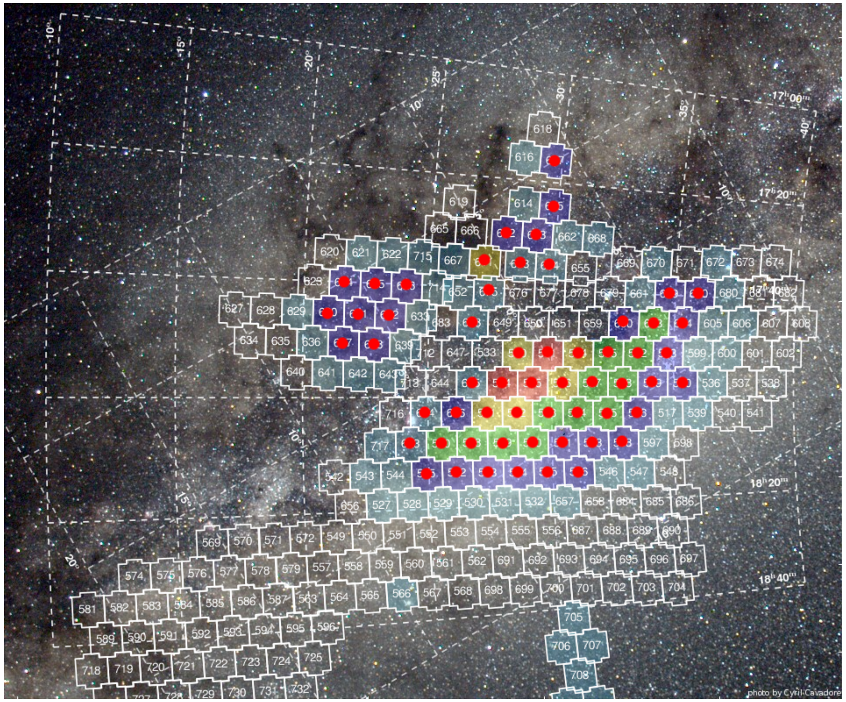
Typical timescales

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



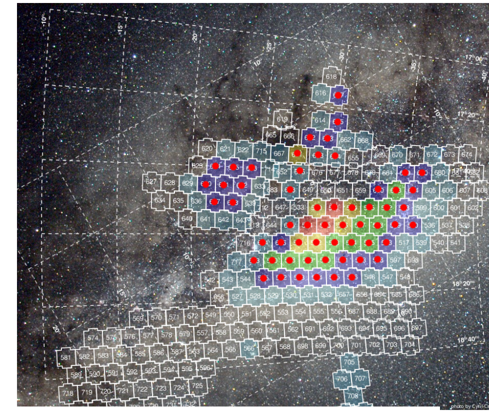
MOA

- 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

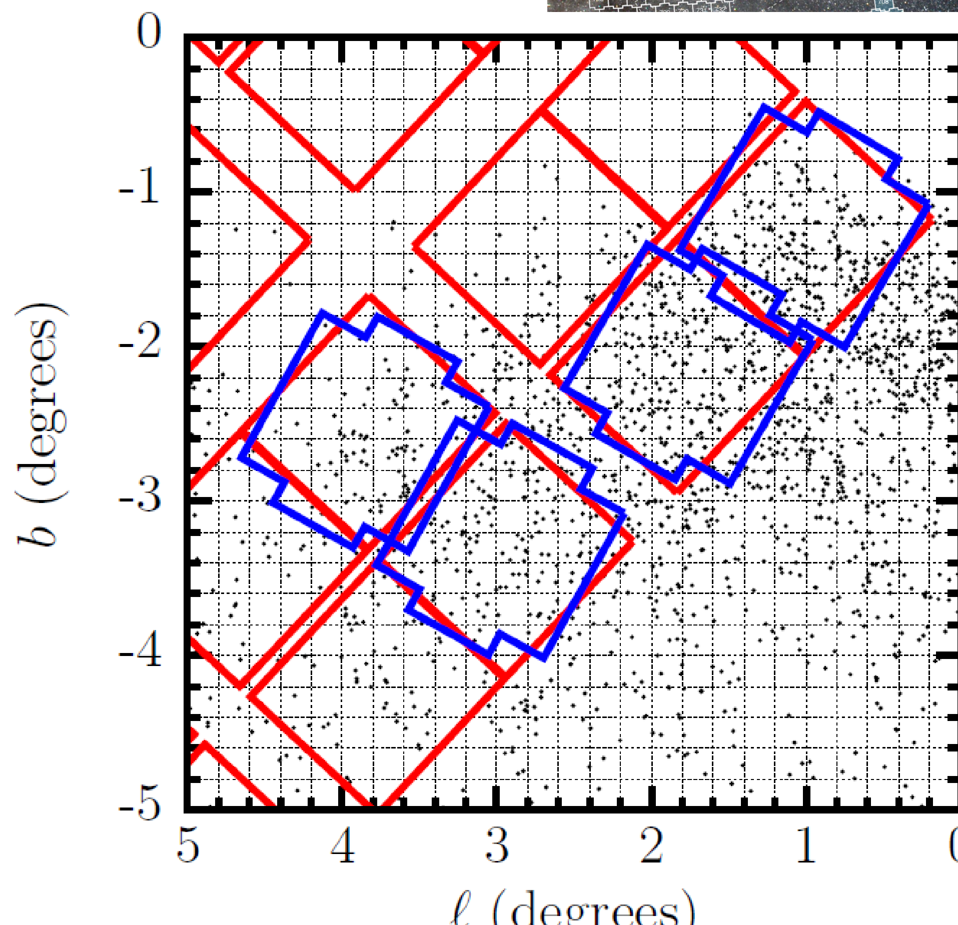
Can OGLE do it?



Operations concept

- **Requires all but K2 fields abandoned**
- Min 4 fields, prob 6
- texp=100s *I*, 200s *V*
- 20s overheads
- 2 *I* exp, 1 *V* exp
- Color cadence:

  30-46 minutes

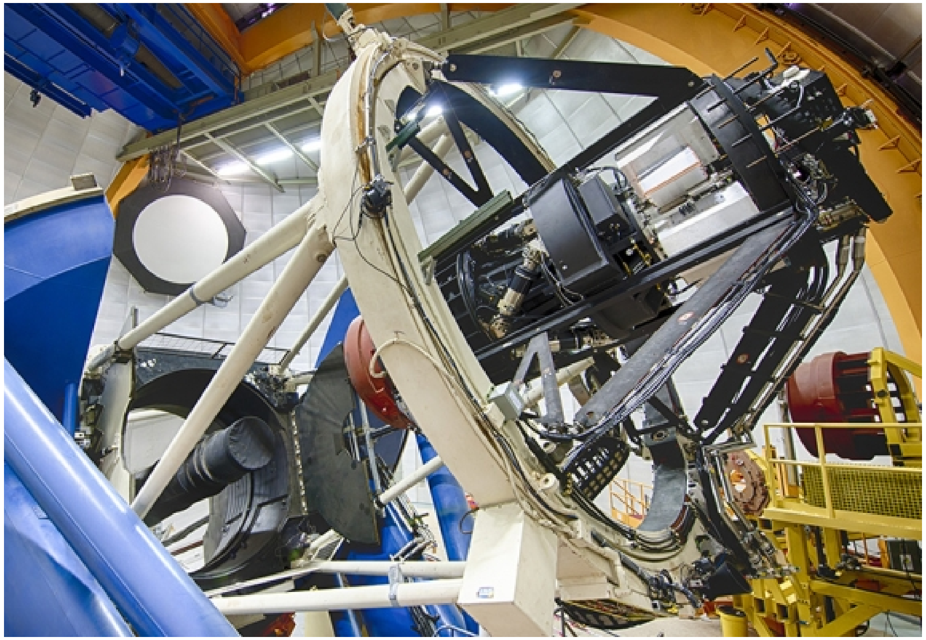


Maybe...

Current options – Shared Time

DECam

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



VST @ Paranal

- 1 deg^2,   2.6 m

Skymapper @ SSO

- 5.2 deg^2,   1.3 m

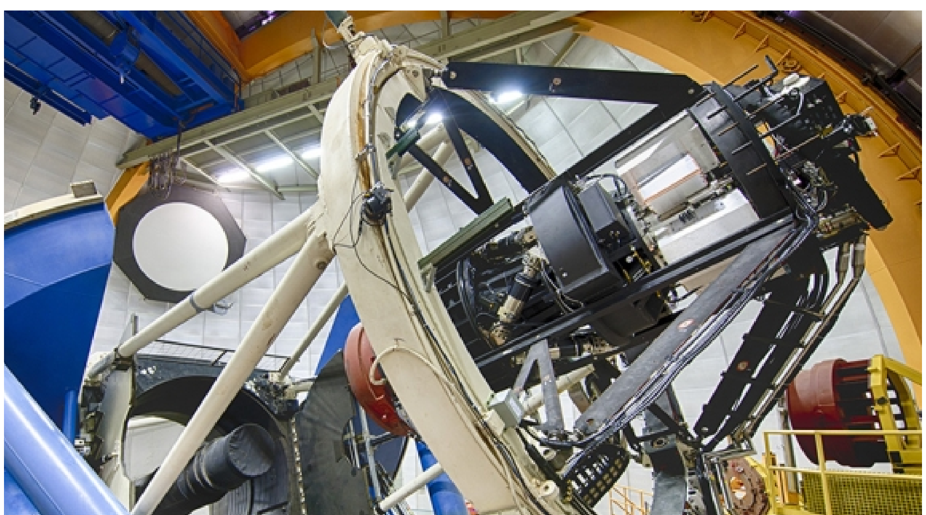
HyperSuprimeCam

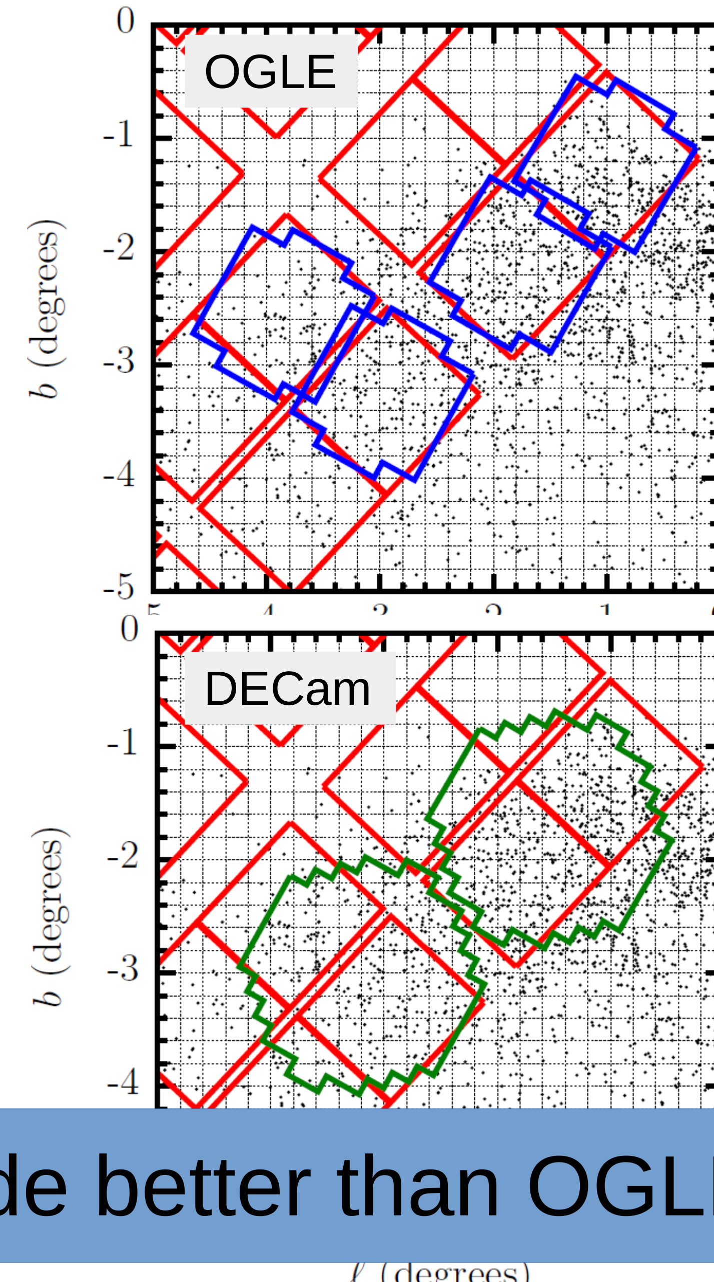
- 1.77 deg^2,   8 m
- Hawaii
- No fast filter changes

DECam for Microlensing

DECam vs OGLE

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





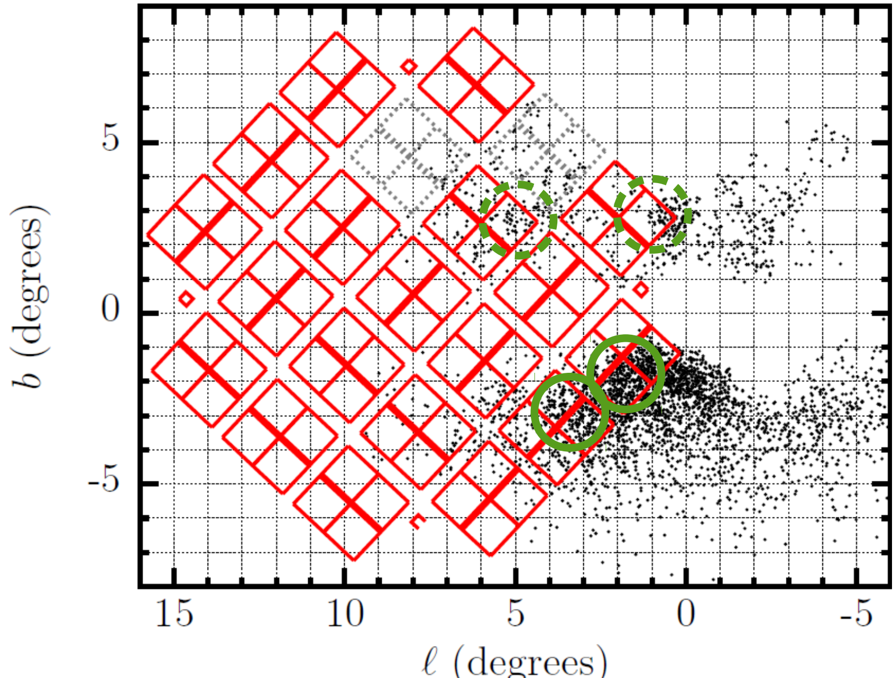
DECam an order of magnitude better than OGLE

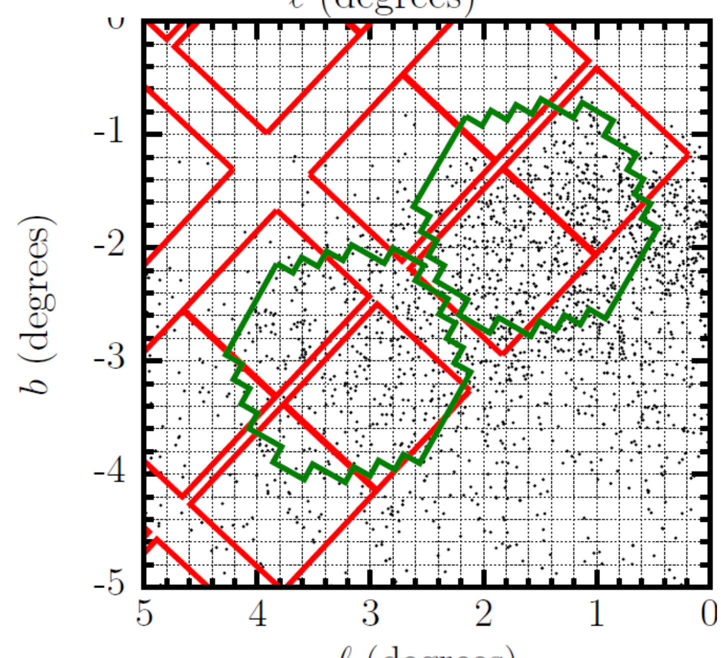
DECam Operations Concept

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

  r-z 2.5--5 minutes

  g 15--30 minutes
- Could replace r with wide VR filter





DECam – Public Data

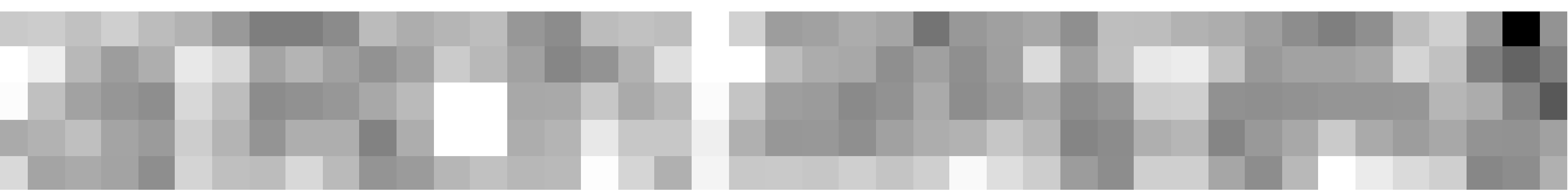
- **Data will be made public on a timescale similar to the Kepler K2 date release** (raw images). Enabling:
  - The development of a larger US microlensing community
  - Deep KBO searches (gets colors + orbits)
  - Asteroseismology of bulge blue stragglers
  - Transiting planets (maybe, colors)
  - Color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

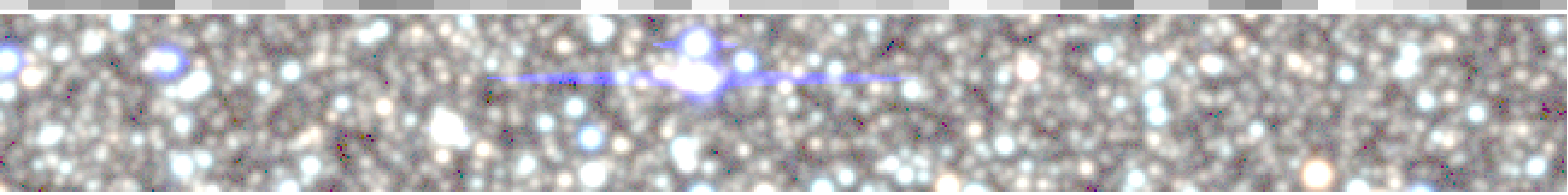
So How Do They Measure Up?

- Need simulations...
- What will Kepler find?
- How many events can be seen from both Kepler and the ground?
- How deep do we need to go?

MaBuLS simulations

- Simulates images
- Generates Microlensing events
- Detection criteria
- Fisher Matrix parameter estimation





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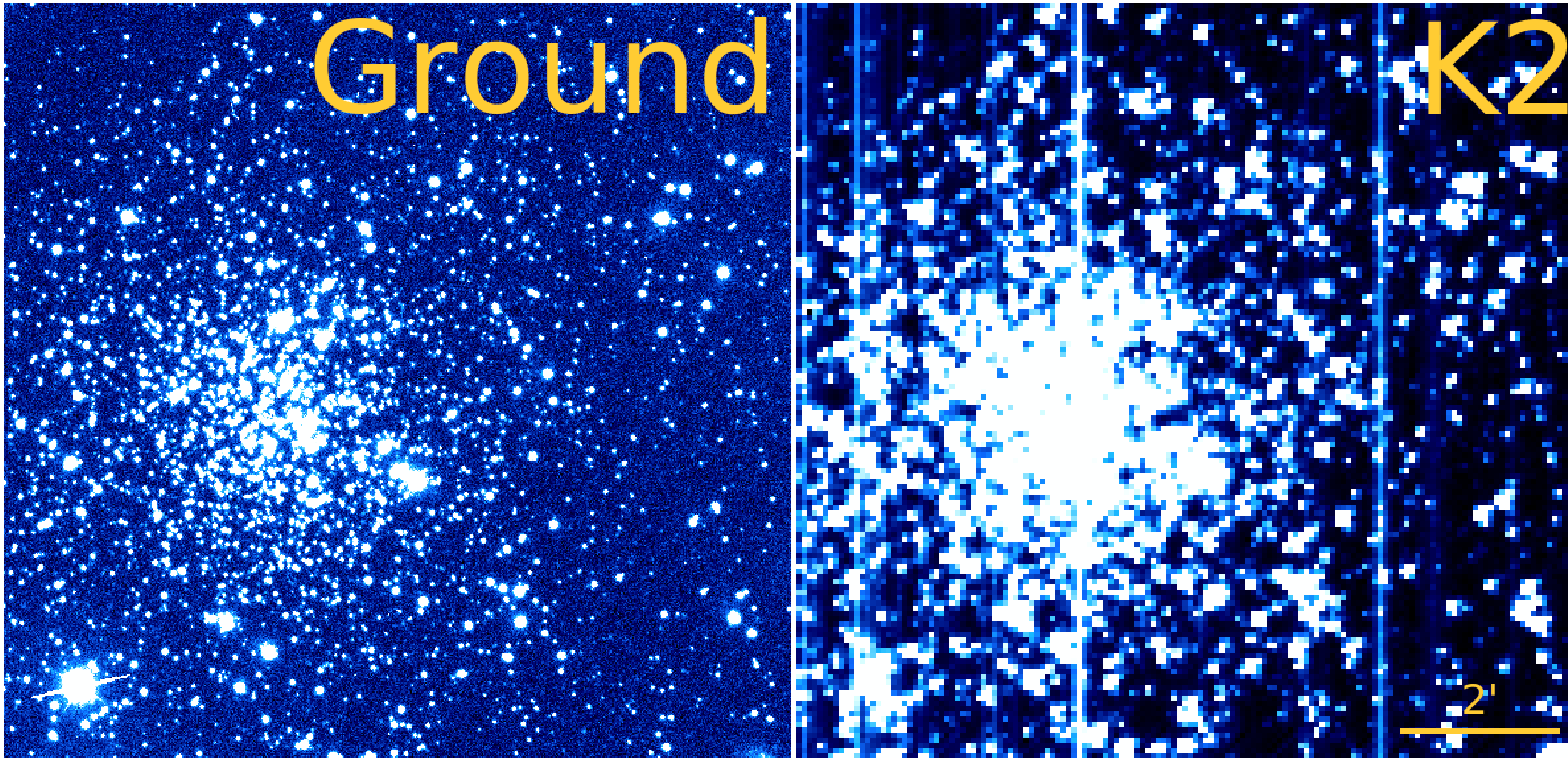
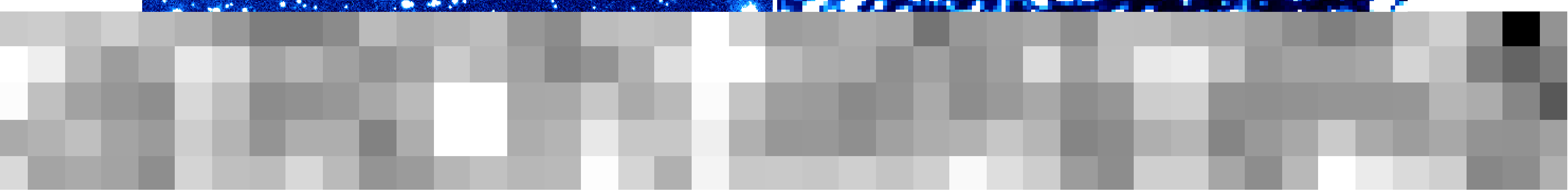
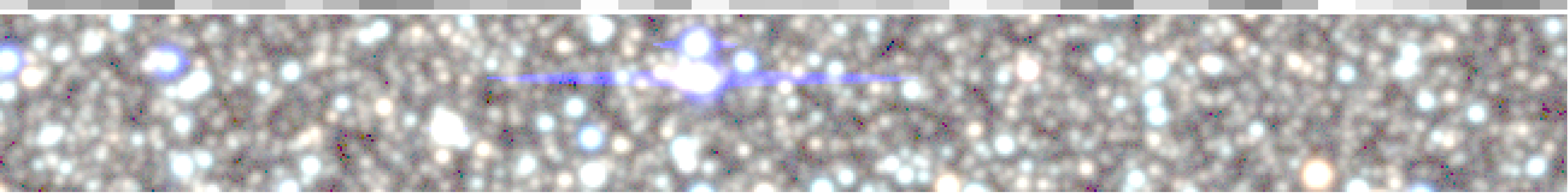
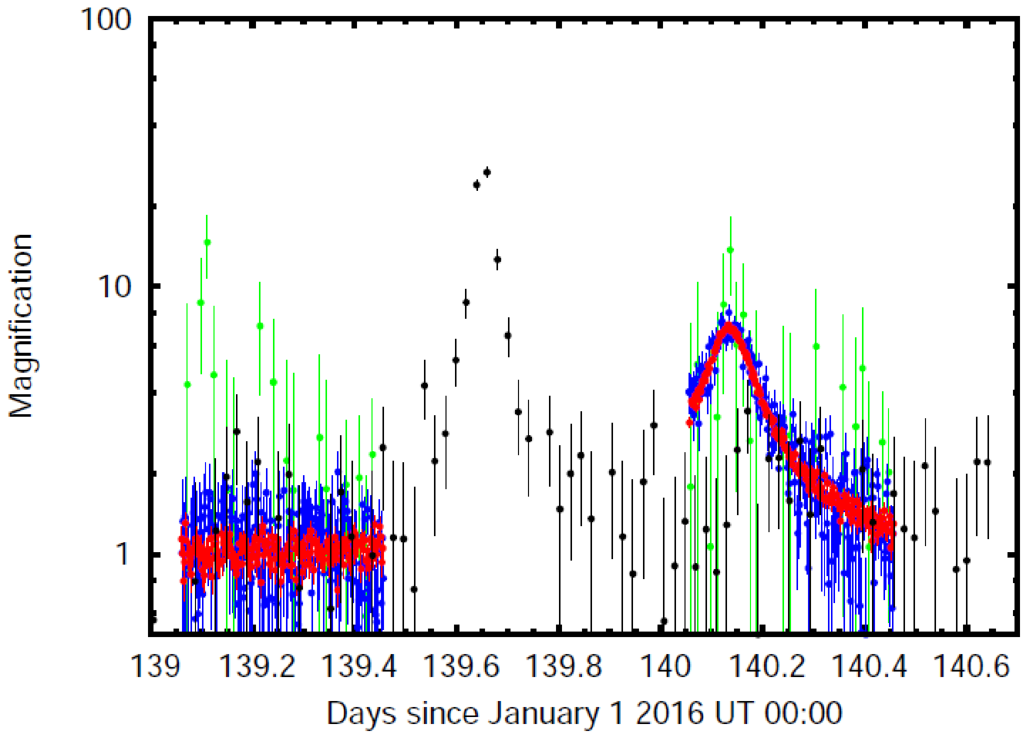


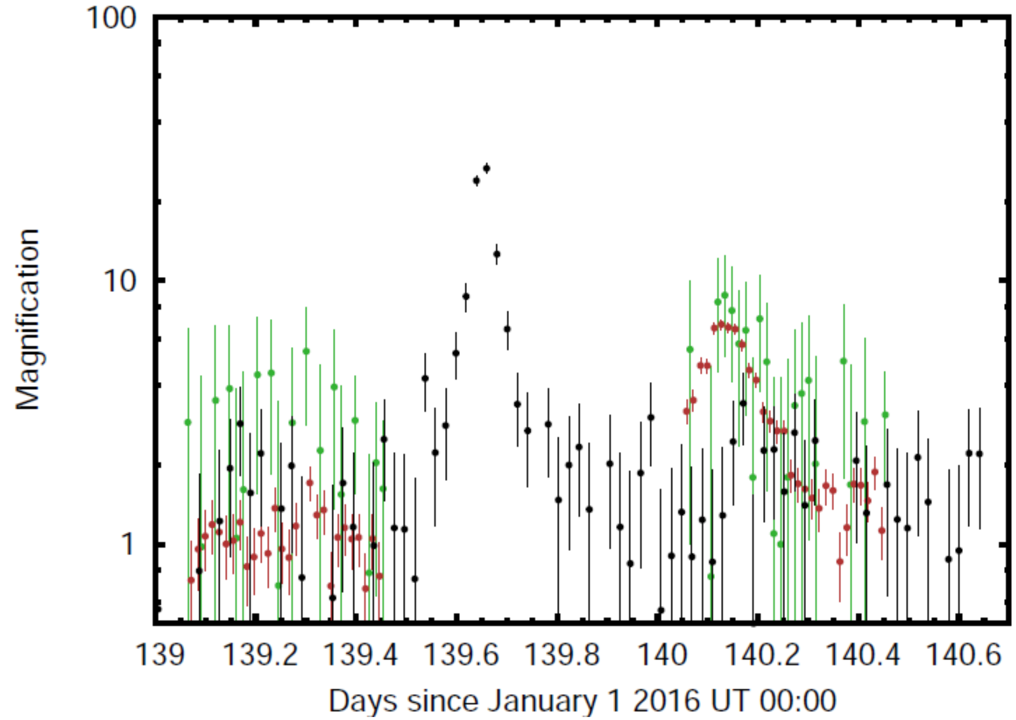




DECam vs OGLE

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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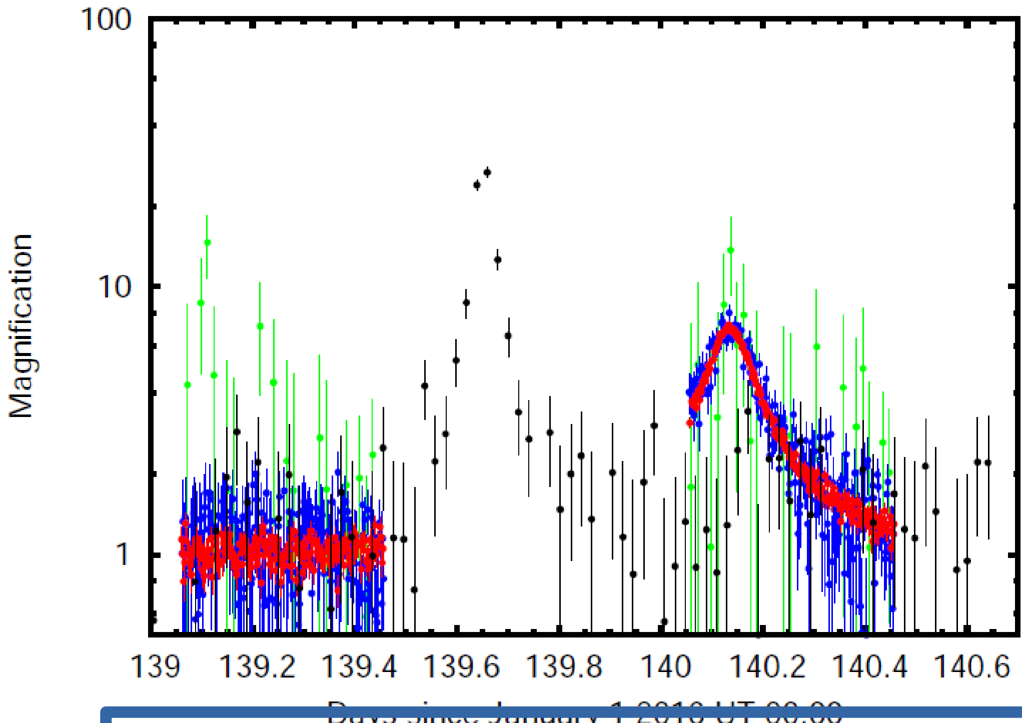

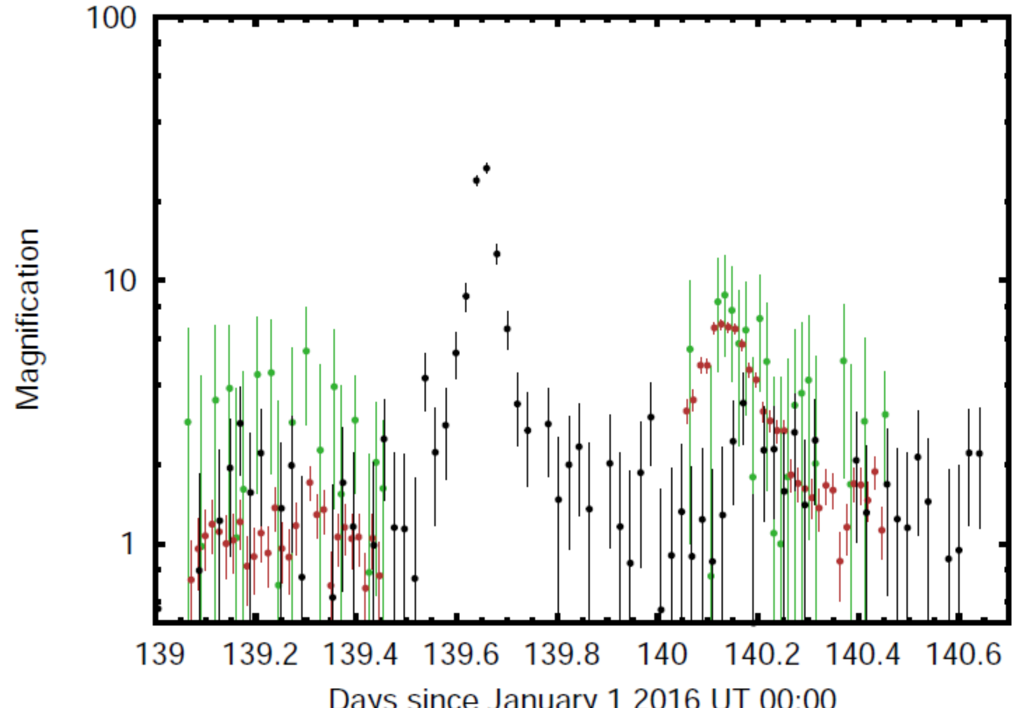

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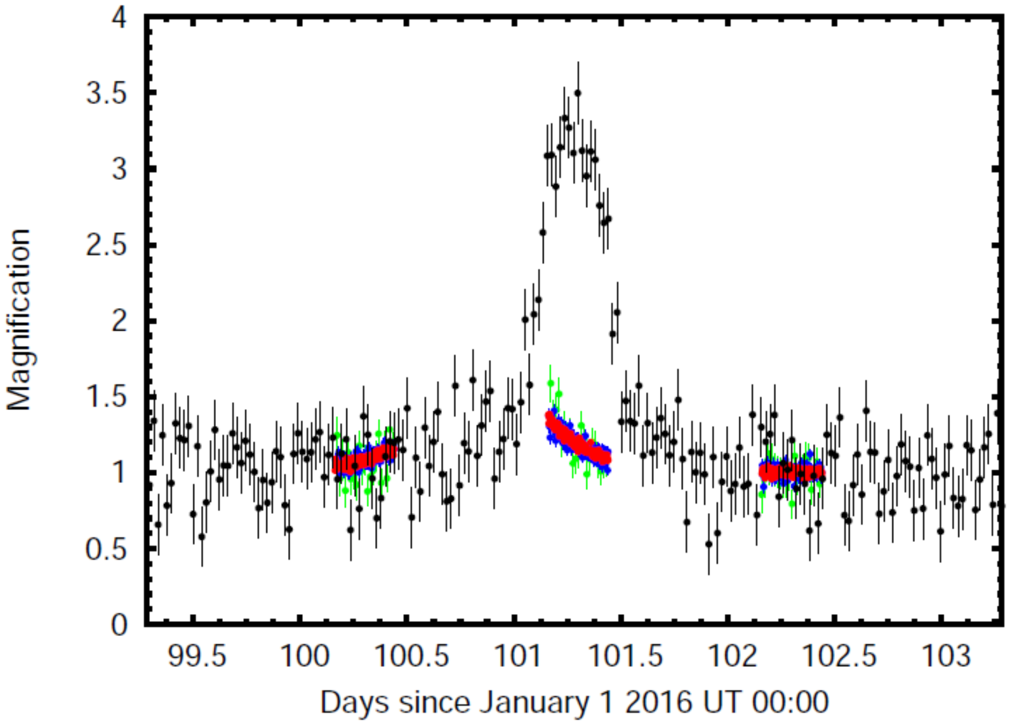
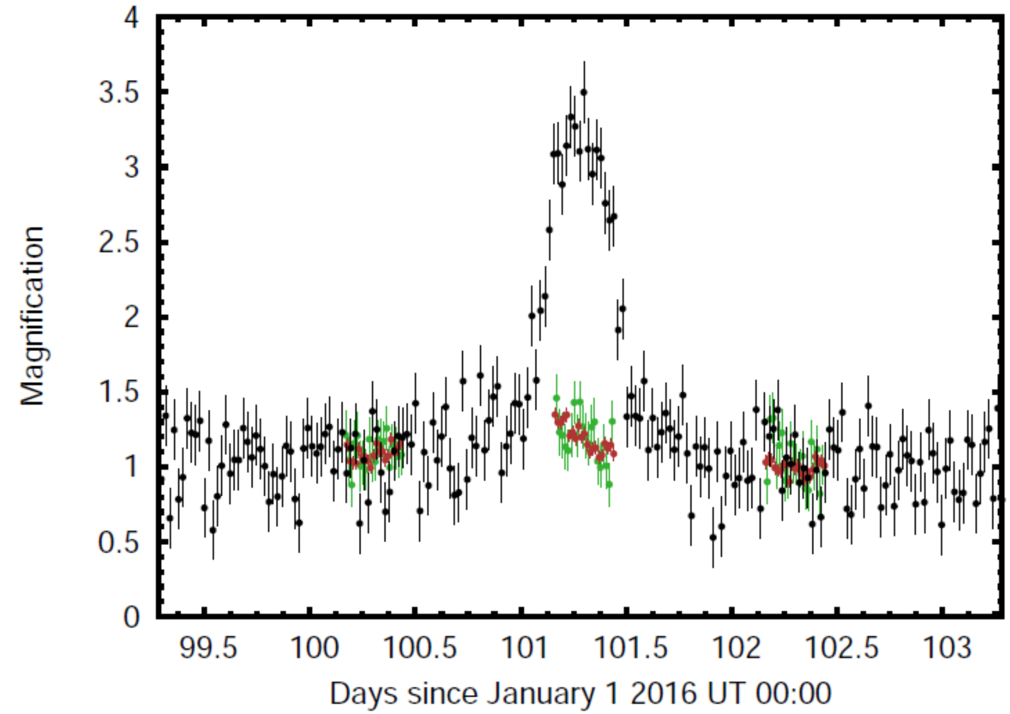
DECam vs OGLE

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

Number of Free Floating Planet Detections

- Assumes 1 per star per mass, 5 sq degrees
- $\Delta X^2 > 500$ for each observatory
- Very rough numbers (sims. not yet complete)

Mass (M_E)	K2	K2+OGLE	K2+DECam
1000	~35	~17	~21
300 Jupiter	~14	~5	~8
100 Saturn	~7	~1.8	~3.4
10	~1	~0.2	~0.3

DECam vs OGLE

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Mass (M_E)	K2	K2+OGLE	K2+DECam
1000	~25	~17	~21
300 Jupiter	~14	~5	~8
100 Saturn	~7	~1.[illegible]	~3.4
10	~1	~0.2	[illegible]

Not Mass Measurements Yet

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***

Takeaway message

- K2's campaign 9 offers a unique opportunity to measure the masses of free-floating planets that is likely ***not to be repeated***
- Free-floating planet masses can only be measured if there is a ***simultaneous high-cadence 2+ color*** survey over the same area
- ***The only instrument that can do this and measure a sample of free-floating planet masses is DECam***