Constraining Primordial Black Hole Dark Matter using Microlensing

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PBH Formation

- First proposed by Hawking (1971) and mentioned by Zel'dovich and Novikov (1966)
- Can form anytime during the early universe when there is an overdensity of 30% or more
- Many ways in which they can form:
  - Due to large primordial inhomogeneities (producing fluctuations which decrease with increasing scale, "designer" inflation, fluctuations with a "running index", due to reheating, etc)
    - Enhanced if there is a soft equation of state (at the quark-hadron era, through a dust-like phase, etc)
  - Through bubble collisions, from collapse of cosmic strings, necklaces, domain walls, etc

PBH DM Mass Ranges

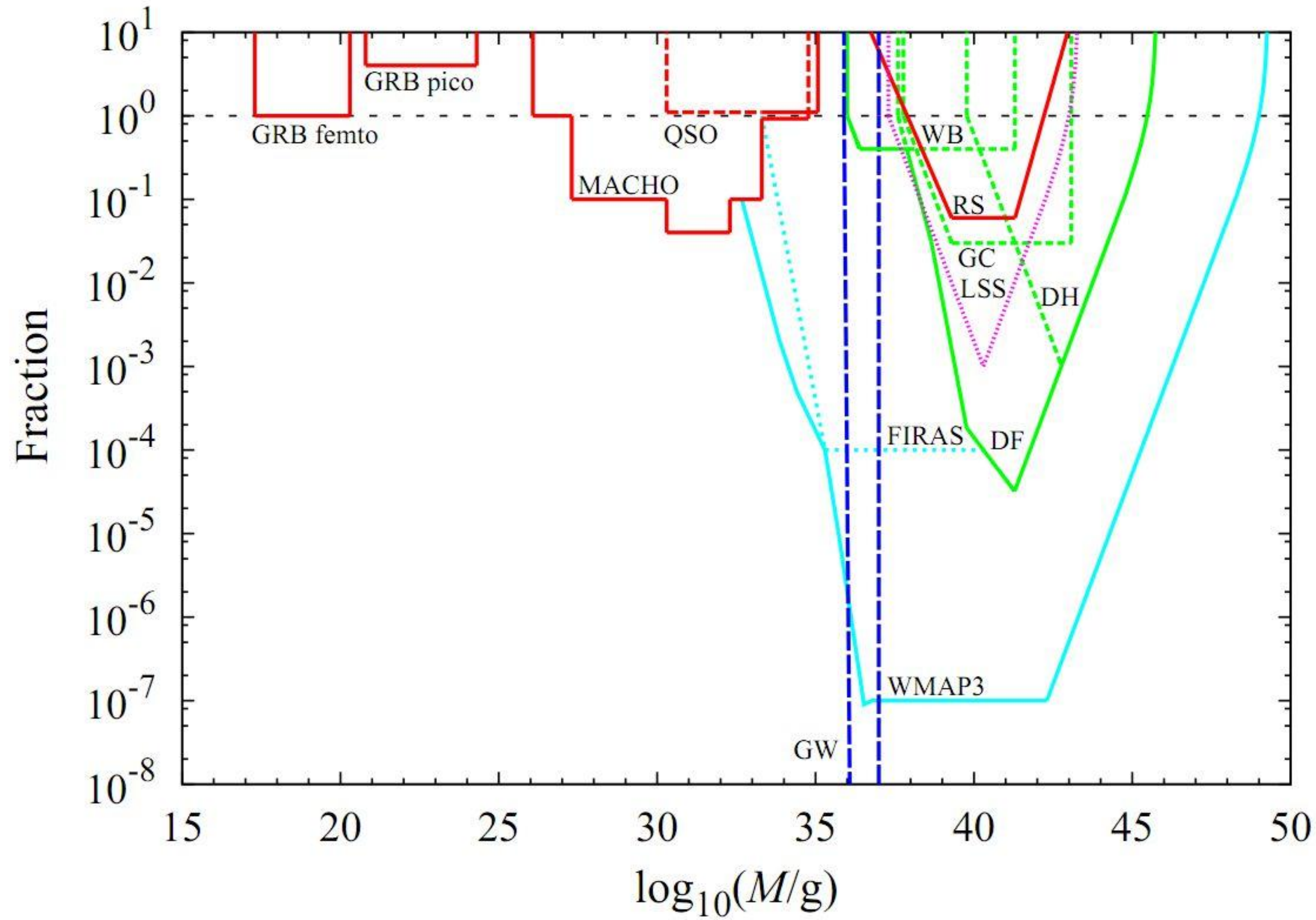
- Most produce a PBH mass equivalent to the mass of the horizon at the time when they form
- $M<10^{15}$g: Evaporated by the age of the Universe due to Hawking radiation
- $M\sim10^{15}$g: Producing photons with energy ~100MeV
- $M>10^{15}$g: DM candidates

PBH Dark Matter

- One of the few Dark Matter candidates of the Standard Model of Particle Physics
- Nonbaryonic – if formed during radiation era
- Dynamically cold

Primordial Black Hole Dark Matter

- One PBH DM constraint window left:



Carr et al. 2010

Primordial Black Hole Dark Matter

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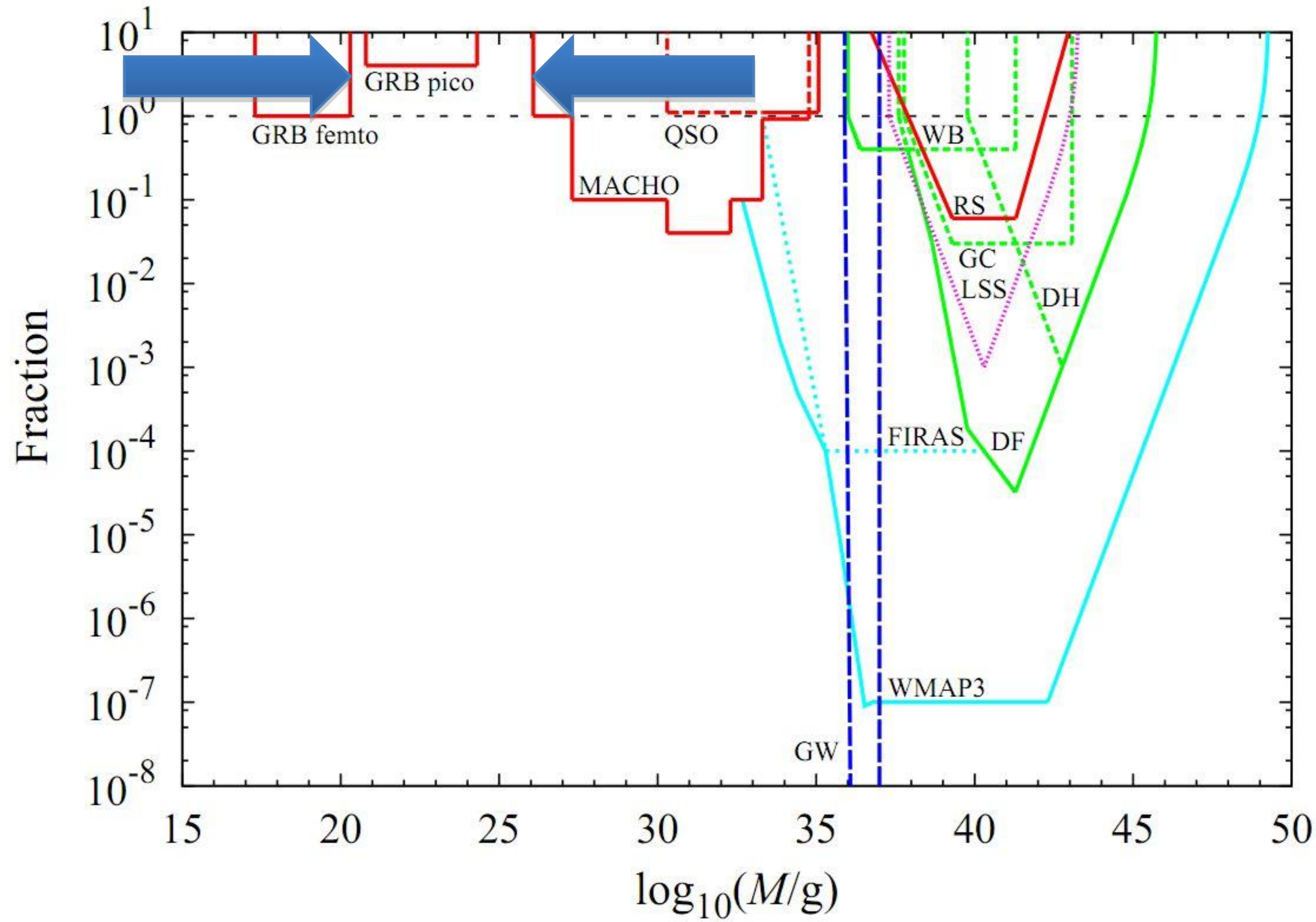
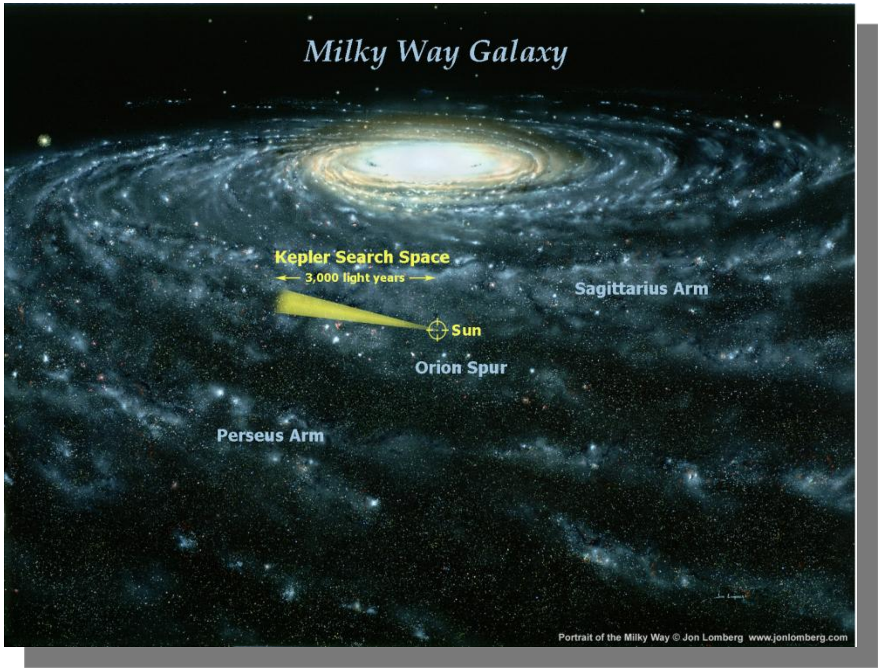


Carr et al. 2010

Kepler Mission

- Kepler will monitor ~160,000 stars at a distance of 1kpc for 3.5 years; naively 8000 times less sensitive but surprising result
- 1 m telescope aperture with 105 deg^2 FOV in an Earth trailing heliocentric orbit
- Photometric measurements of stars every 30 min
- Launched in March 2009, points at Cygnus-Lyra region
- Bandpass: 430-890nm FWHM



http://kepler.nasa.gov

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Microlensing of Kepler Stars as a Method of Detecting Primordial Black Hole Dark Matter

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If the dark matter consists of primordial black holes (PBHs), we show that gravitational lensing of stars being monitored by NASA's Kepler search for extrasolar planets can cause significant numbers of detectable microlensing events. A search through the roughly 150 000 light curves would result in large numbers of detectable events for PBHs in the mass range $5 \times 10^{-10} M_\odot$ to $10^{-4} M_\odot$. Nondetection of these events would close almost 2 orders of magnitude of the mass window for PBH dark matter. The microlensing rate is higher than previously noticed due to a combination of the exceptional photometric precision of the Kepler mission and the increase in cross section due to the large angular sizes of the relatively nearby Kepler field stars. We also present a new formalism for calculating optical depth and microlensing rates in the presence of large finite-source effects.

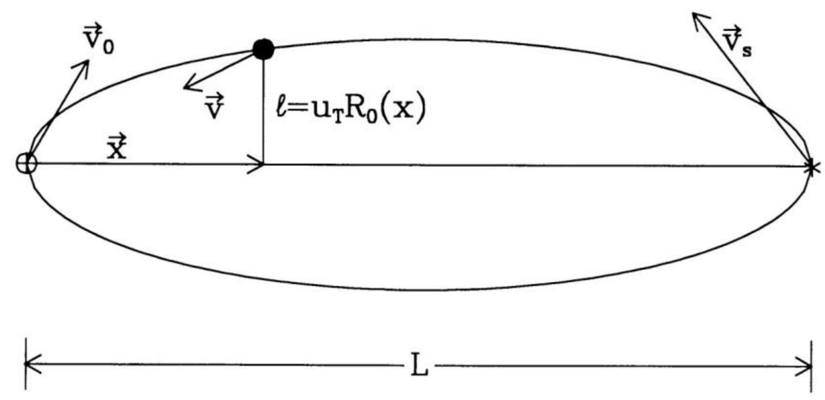
Analytic Estimate: Extreme Precision of Kepler

- Allows a magnification threshold of A_T=1.001 or lower!
- The optical depth increases for lower A_T

$$\tau = \int n \sigma dl$$

$$\sigma = \pi u_T^2 r_E^2$$

$$\rho(D_L) = n M(D_L)$$

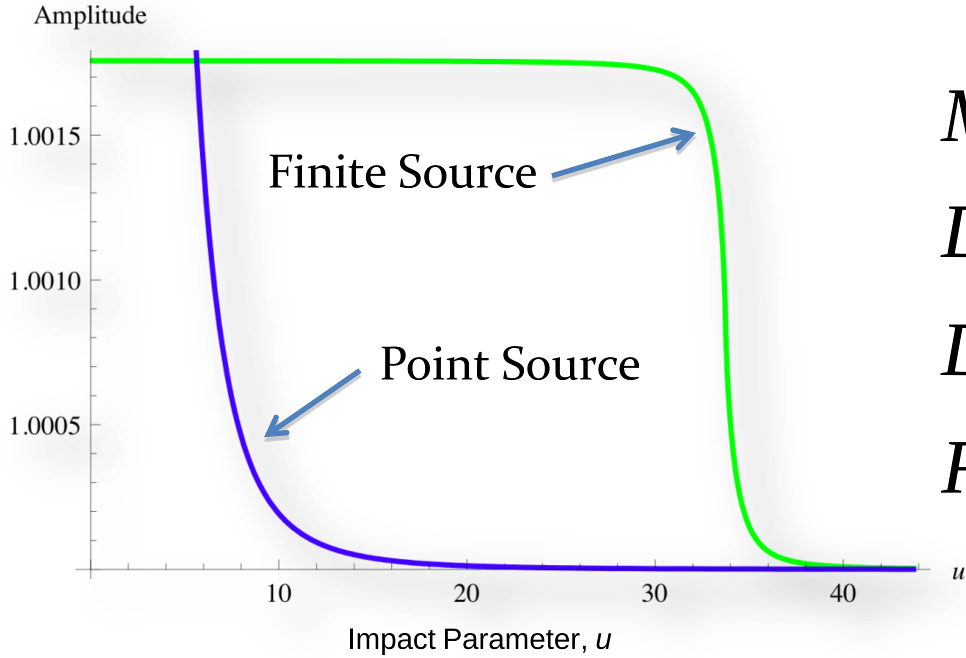


Griest '91

Event Rate: $\Gamma = \tau / < t_e >$

Analytic Estimate: Finite-Source Effects

- Paczynski '86 and Griest '91: mostly considered point-sources, looking for a magnification of LMC stars of 34% when lens is within 1 Einstein ring radius
- Kepler source stars: u_T dominated by projected star radius, producing a bigger microlensing tube
- Overall effect: Amplitude lowered but longer event duration (Witt and Mao '94)



$$M = 10^{-9}$$
$$D_s = 1kpc$$
$$D_L = 0.3kpc$$
$$R_* = 1R_\odot$$

New Formalism for Calculating Microlensing Rates

- There is a maximum distance to the lens, x_{max} for A to be detectable

$$x = \frac{D_L}{D_S} \to 1: \quad A_{\max} \to 1 \quad \text{since } u_* \to \infty$$

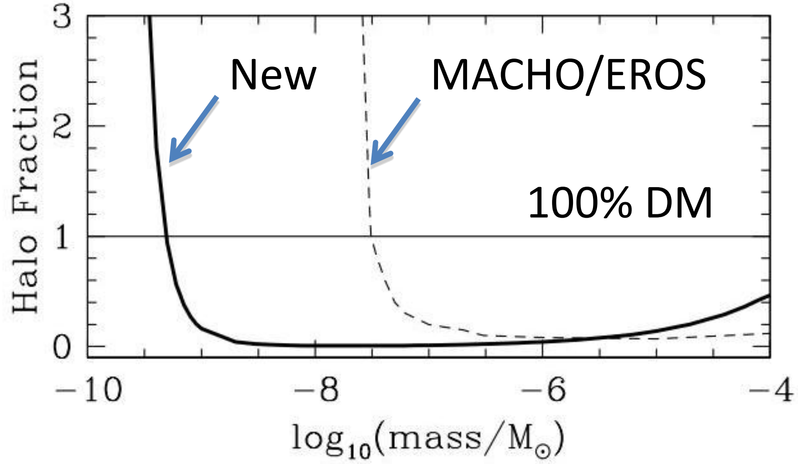
- Assume a constant DM density along the line-of-sight and a Maxwellian velocity distribution
- Require 4 sequential measurements 3 sigma above avg (at least 2hr duration)
  - Therefore, must integrate a differential event rate over a relevant range of event durations:

$$\frac{d\Gamma}{dt_e} = \frac{\rho}{m} D_S v_c^2 \int_0^{x_{\max}} dx \beta'^2 g(\beta')$$

$$g(\beta') = \int_0^1 dy\, y^{3/2}(1-y)^{-1/2} e^{-\beta' y} \qquad y = v_r^2 / (\beta' v_c^2) \qquad \beta = 4 r_E^2 u_{thresh}^2 / (t_e^2 v_c^2)$$

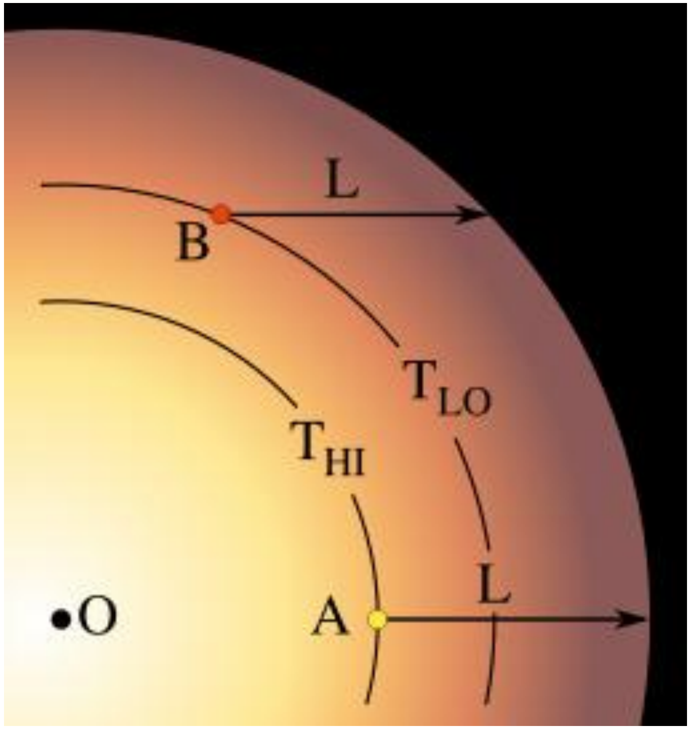
Closing the Window

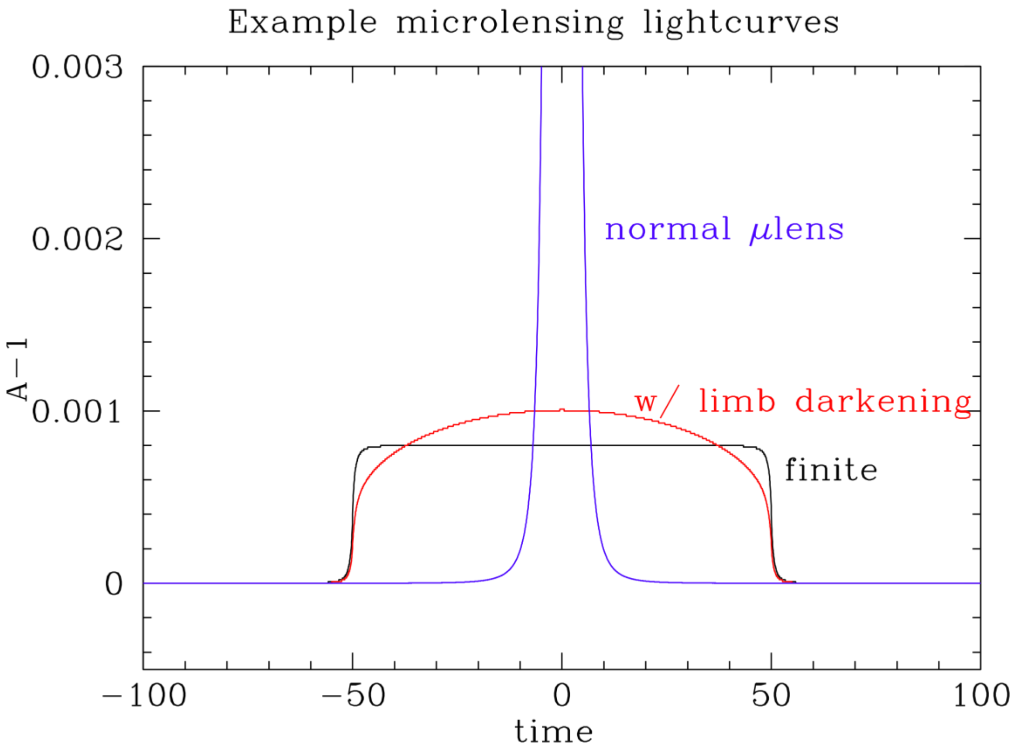
- Analyzed a sample of ~5000 stars and if this technique is used, it has the potential to close ~40% of the window!



K. Griest, M. J. Lehner, **A. M. Cieplak**, and Bhuvnesh Jain, Microlensing of Kepler Stars as a Method of Detecting Primordial Black Hole Dark Matter, Phys. Rev. Lett. 107, 231101 (2011).

Addition of Limb Darkening





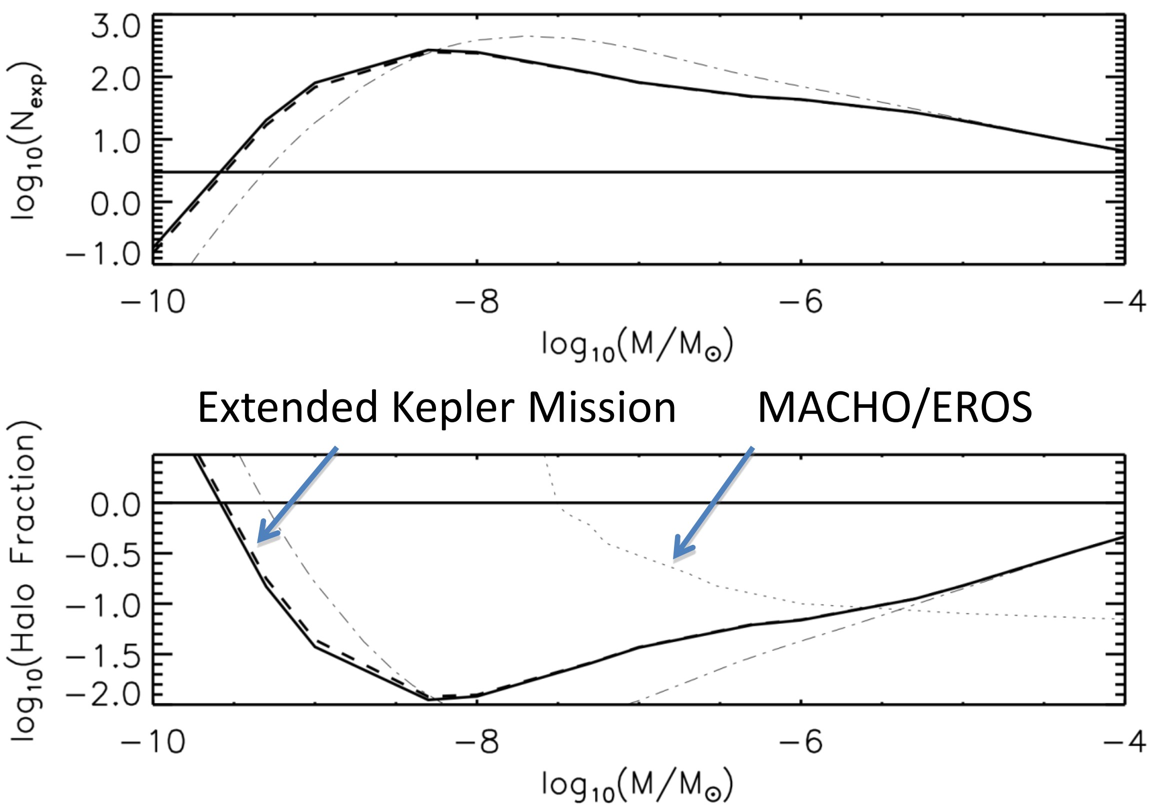
Two effects:

1)Increasing amplitude increases x, and therefore rate of detection

- For a typical Kepler star (R ~ 1 $R_{\odot}$) xmax = 1 already achieved without limb-darkening

2)Reduces event duration: $\tau \sim u_T^2$ so changing impact parameter impacts optical depth in quadrature, therefore should lower rate of detection

Number of Expected Events with Limb Darkening



A. M. Cieplak and K. Griest. ApJ 2013 accepted.

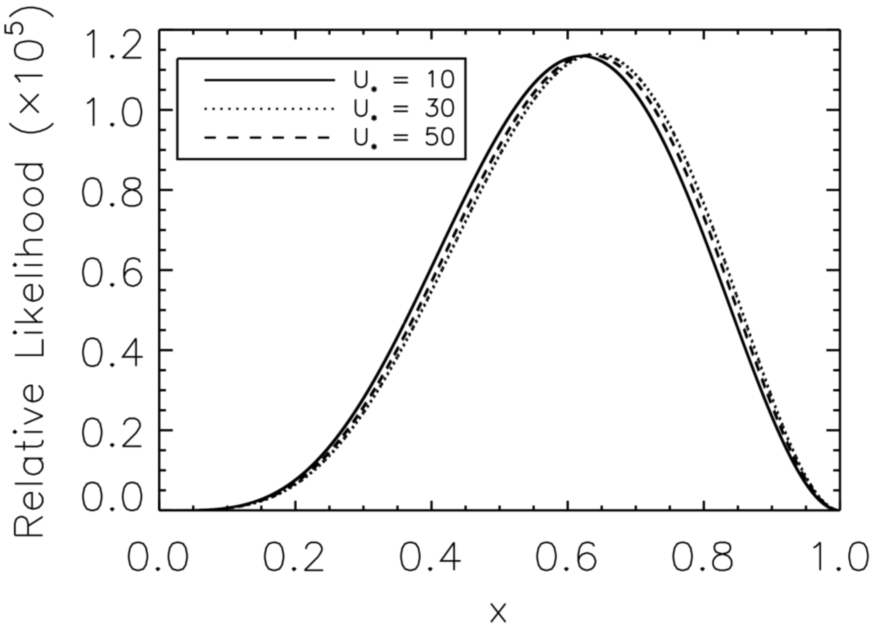
- Analyzed the 156,848 stars monitored in 3rd quarter of Kepler data

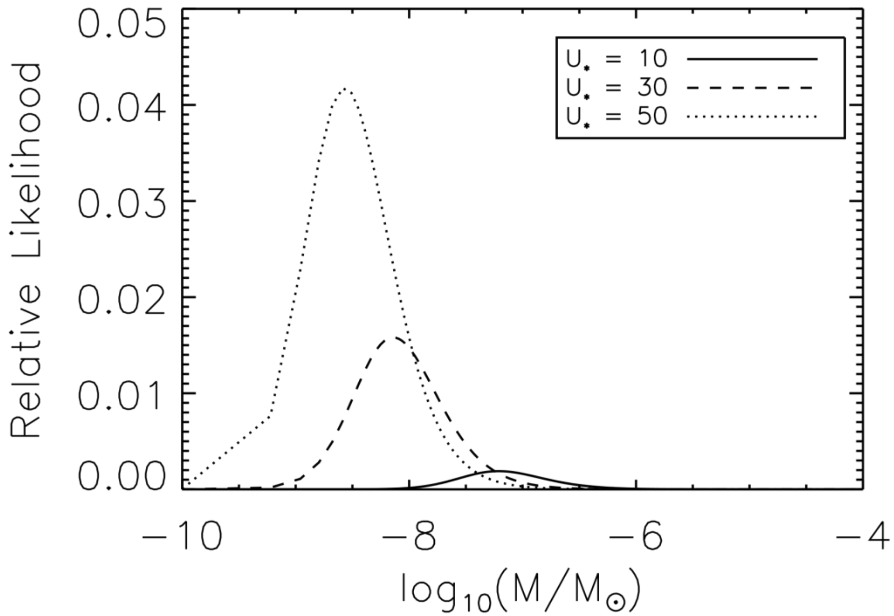
- Assumed 7.5 years of monitoring with 25% of the dwarf stars and 95% of giants discarded as variable (Ciardi et al. 2011)

- Set u_T as the threshold impact parameter for a limb-darkened lightcurve with linear limb coefficients calculated using model grid developed by Sing 2010

Detectable parameters

What if Microlensing Events are detected?





It will not be easy to determine the distances to the lens.

The product of these likelihood functions would give us an estimate of the PBH DM!

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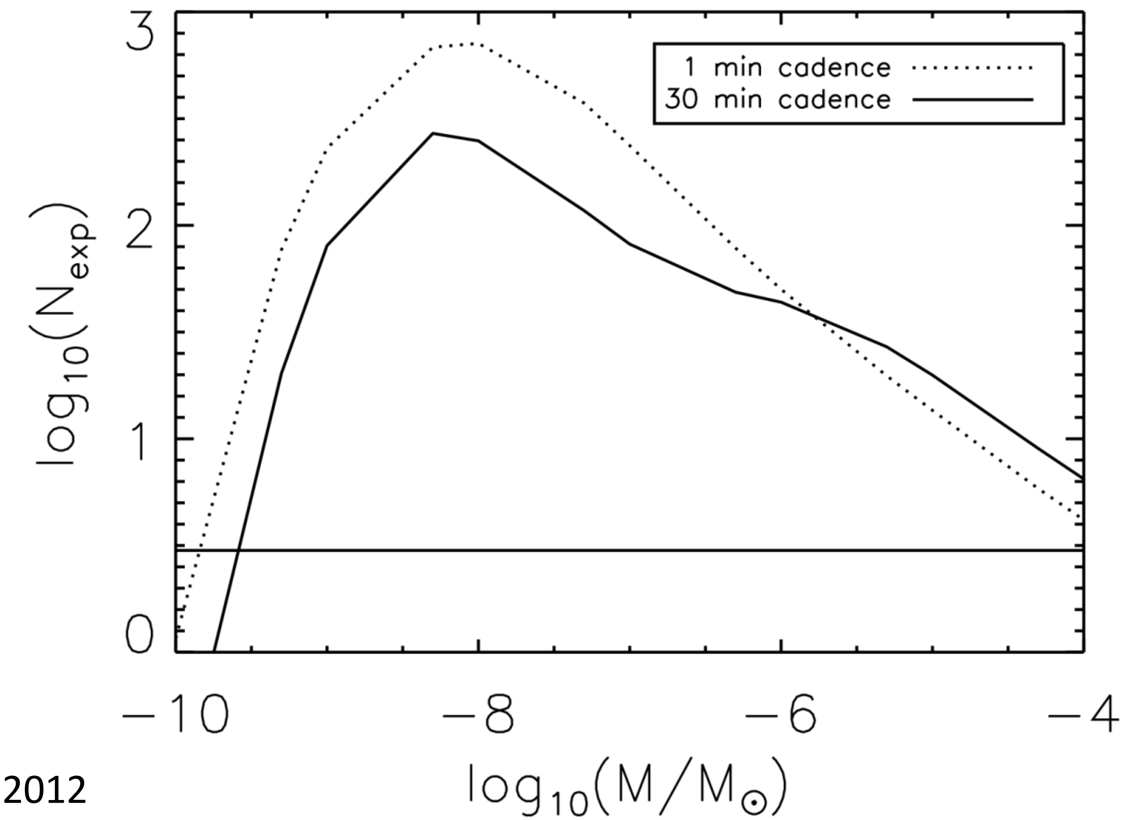
Cadence

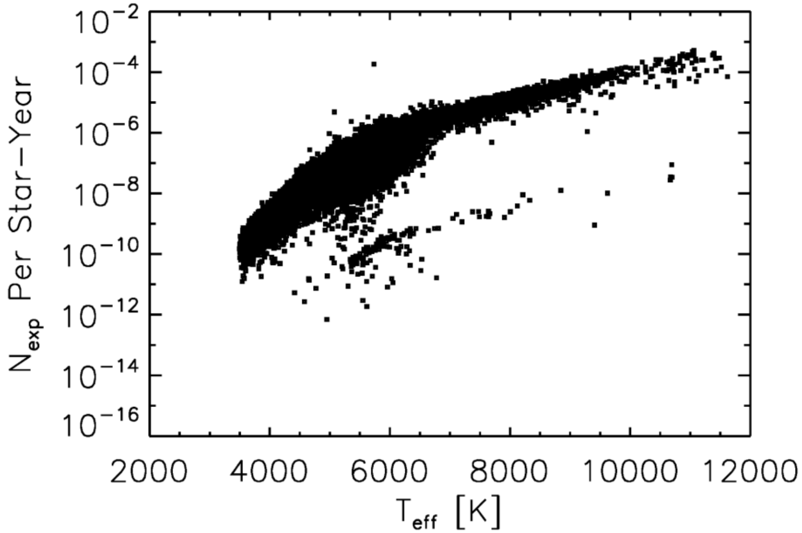


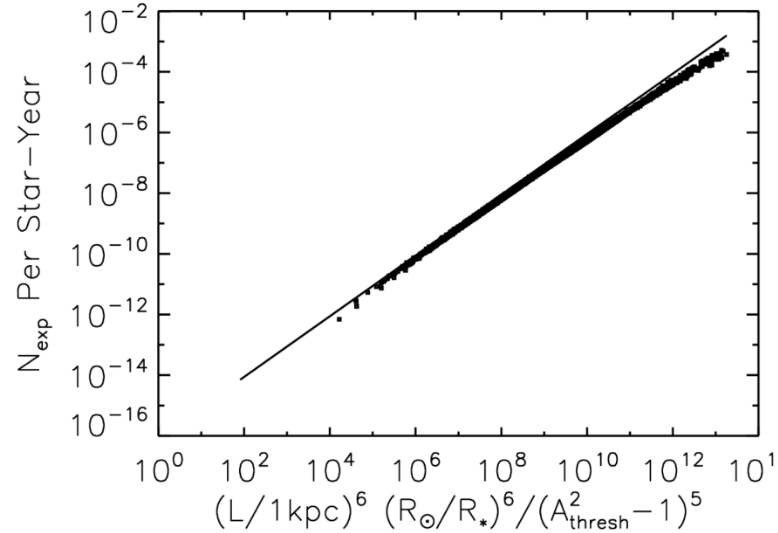
A. M. Cieplak & K. Griest 2012

Reducing the cadence also increases the Poisson average error on each flux measurement. Therefore only modest increase in sensitivity!

Approximation for Future Star Selection

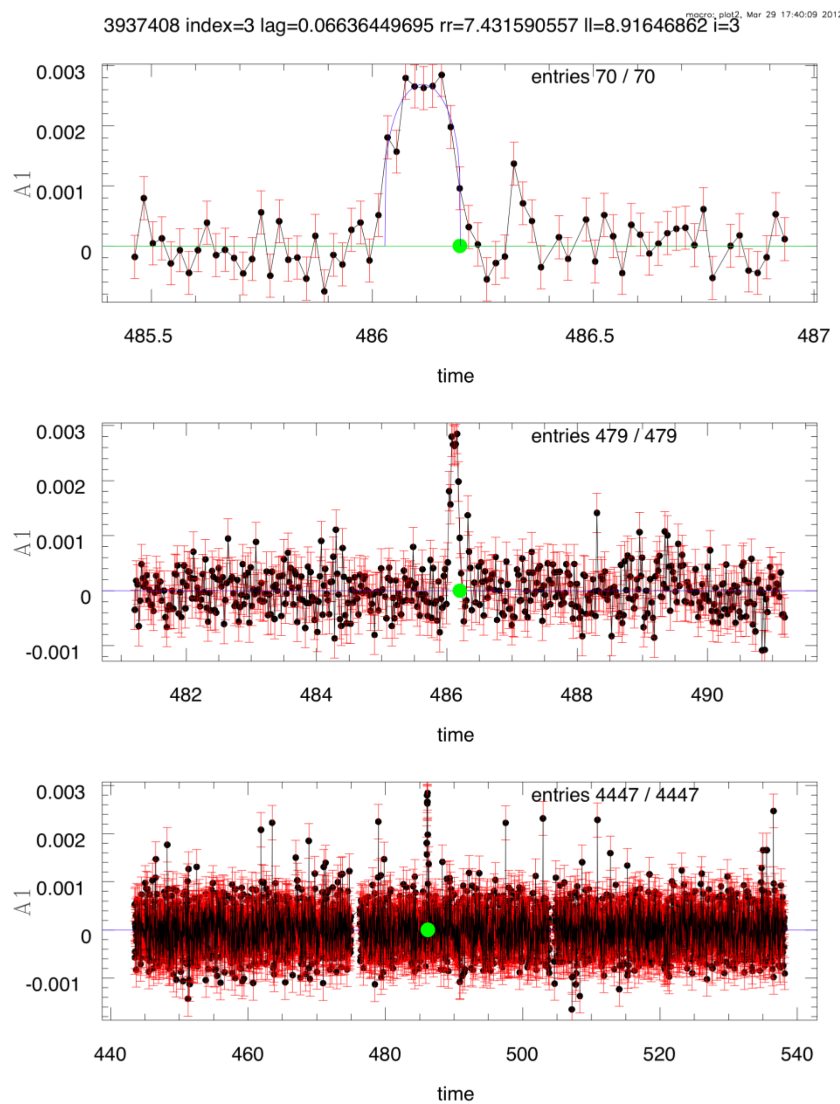
$\Gamma \sim T_{eff}^{12}$



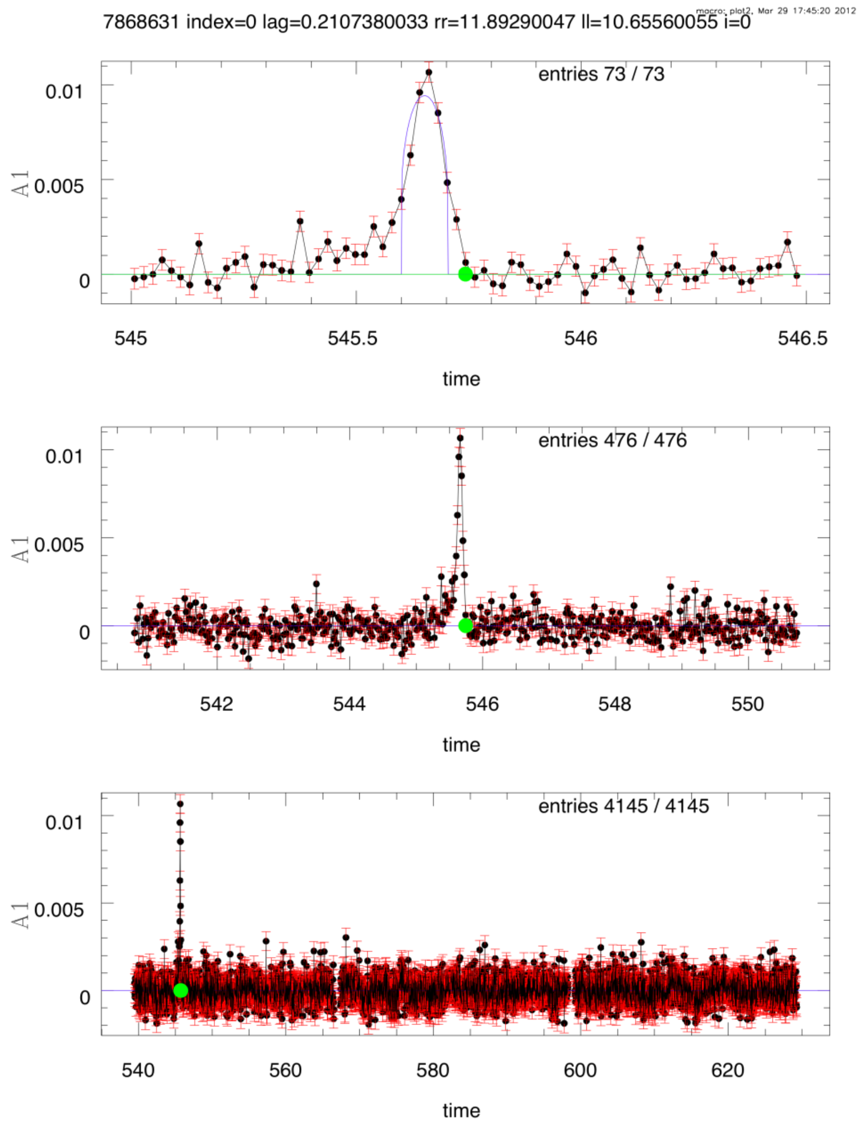


$$\Gamma \approx 2.63\times10^{20}\left(\frac{L}{1kpc}\right)^6\left(\frac{R_*}{R}\right)^6\left(\frac{M}{M_\otimes}\right)^4\left(\frac{1hr}{t_{\min}}\right)^3\frac{1}{\left(A_{thresh}{}^2-1\right)^5}\frac{1}{year}$$

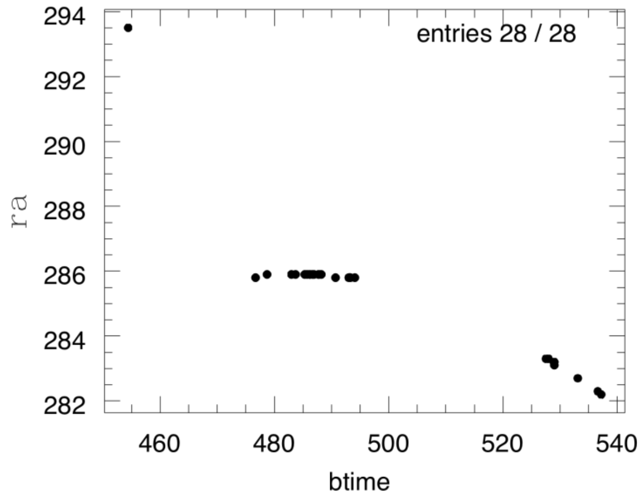
First Look at the Lightcurves

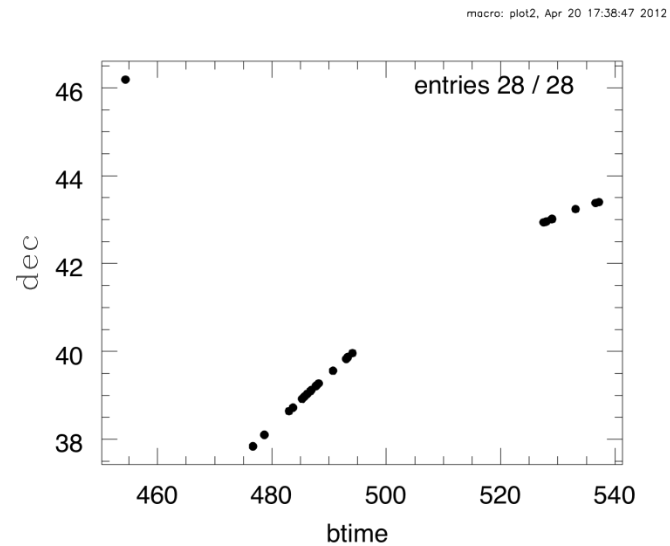


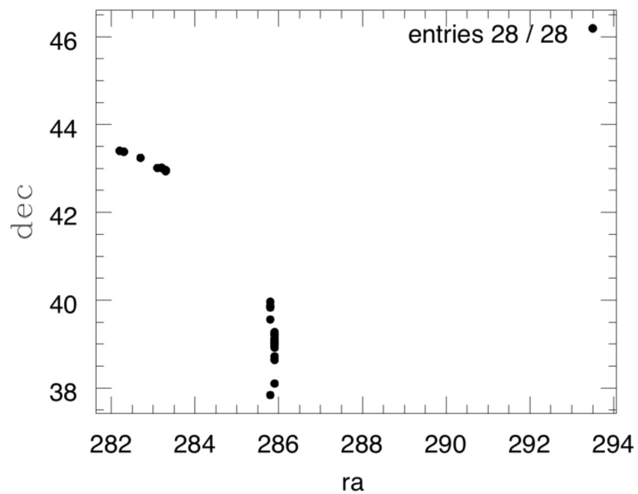
First Look at Lightcurves



Comet!



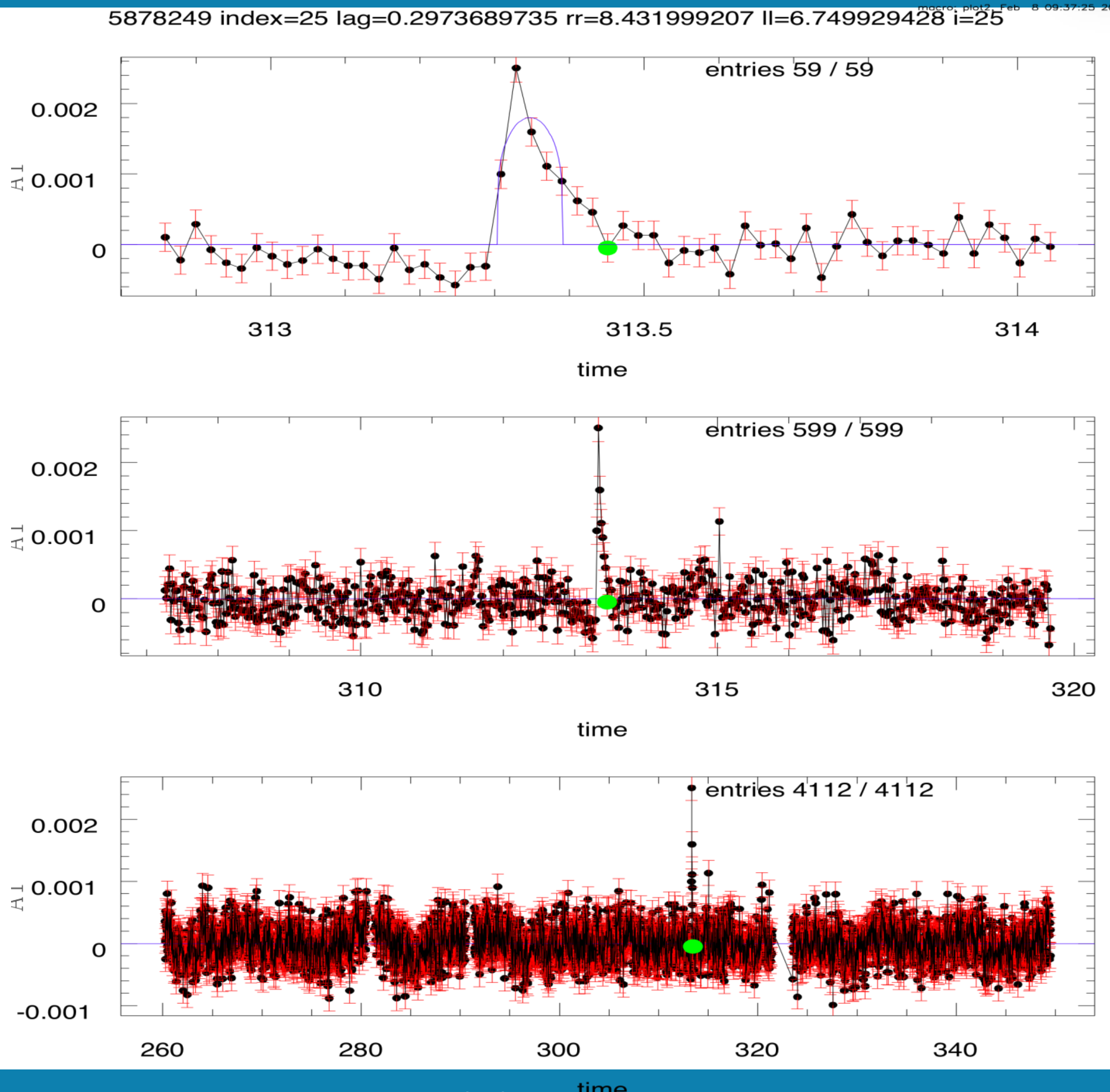




Comet C/2206 Q1 (McNaught)

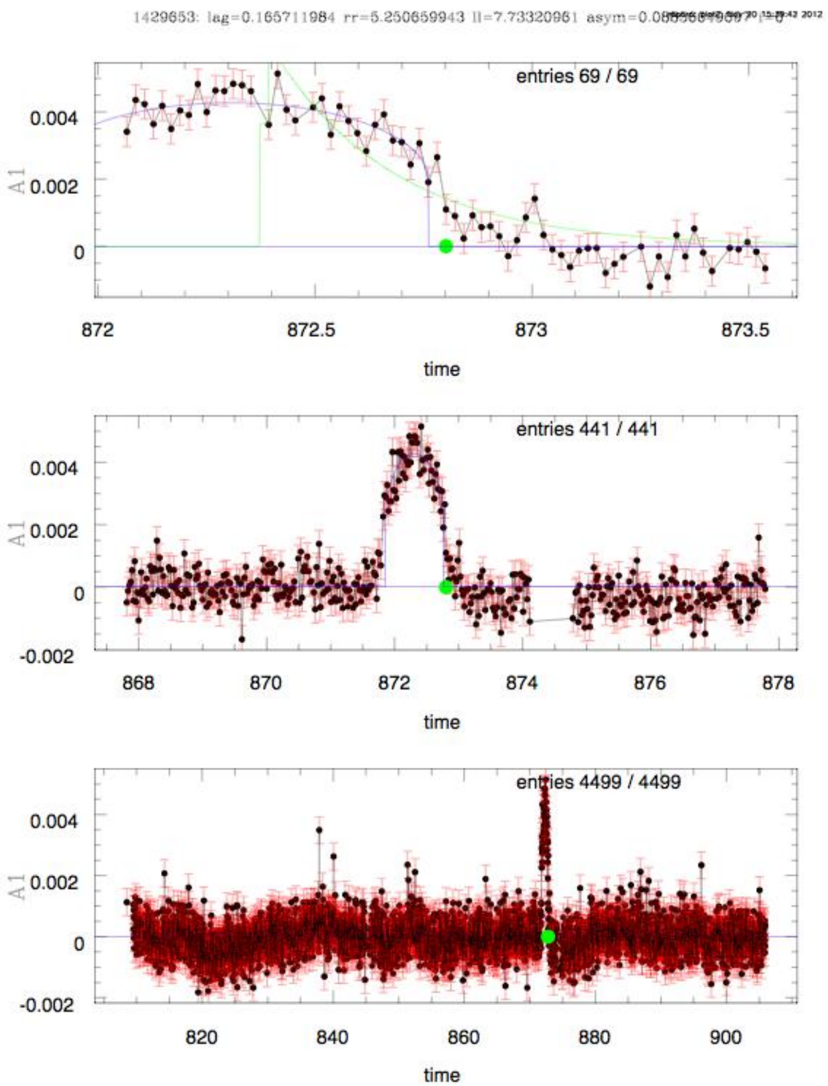
Constant velocity:
16 arcseconds/hour = 3.3 km/s (distance/1AU)

Stellar flares

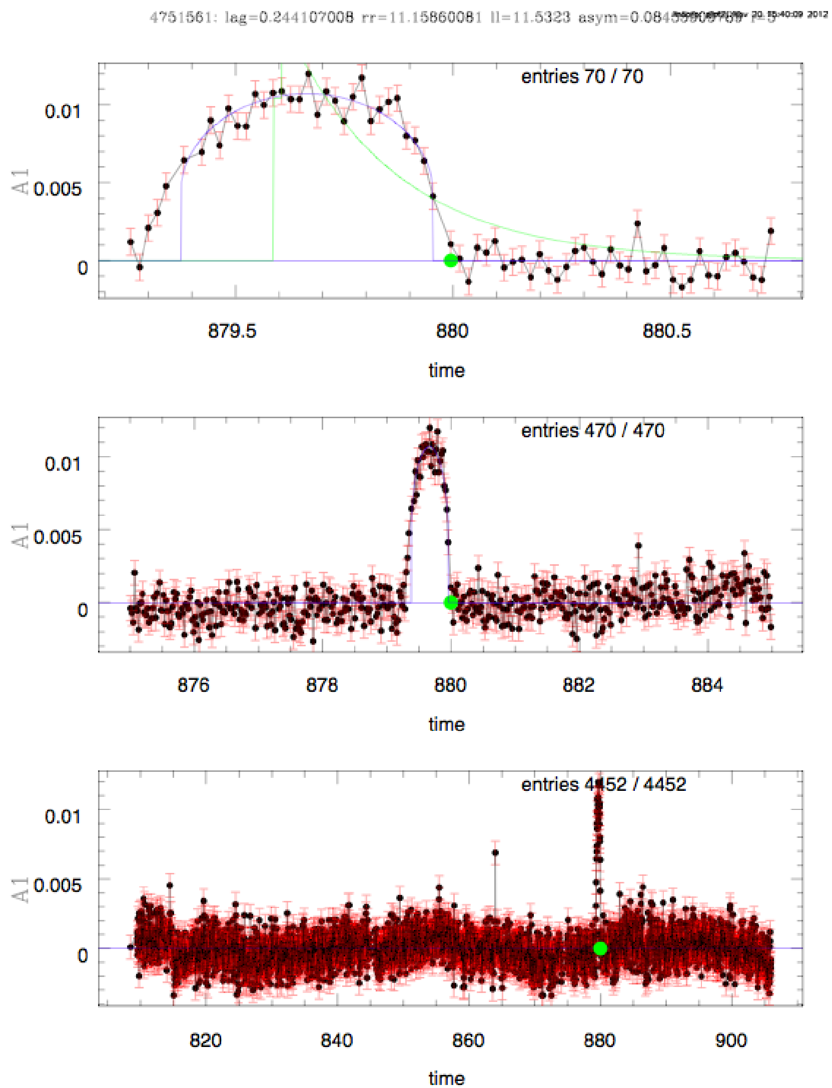


Main source of background noise. Should be asymmetric, like this one.

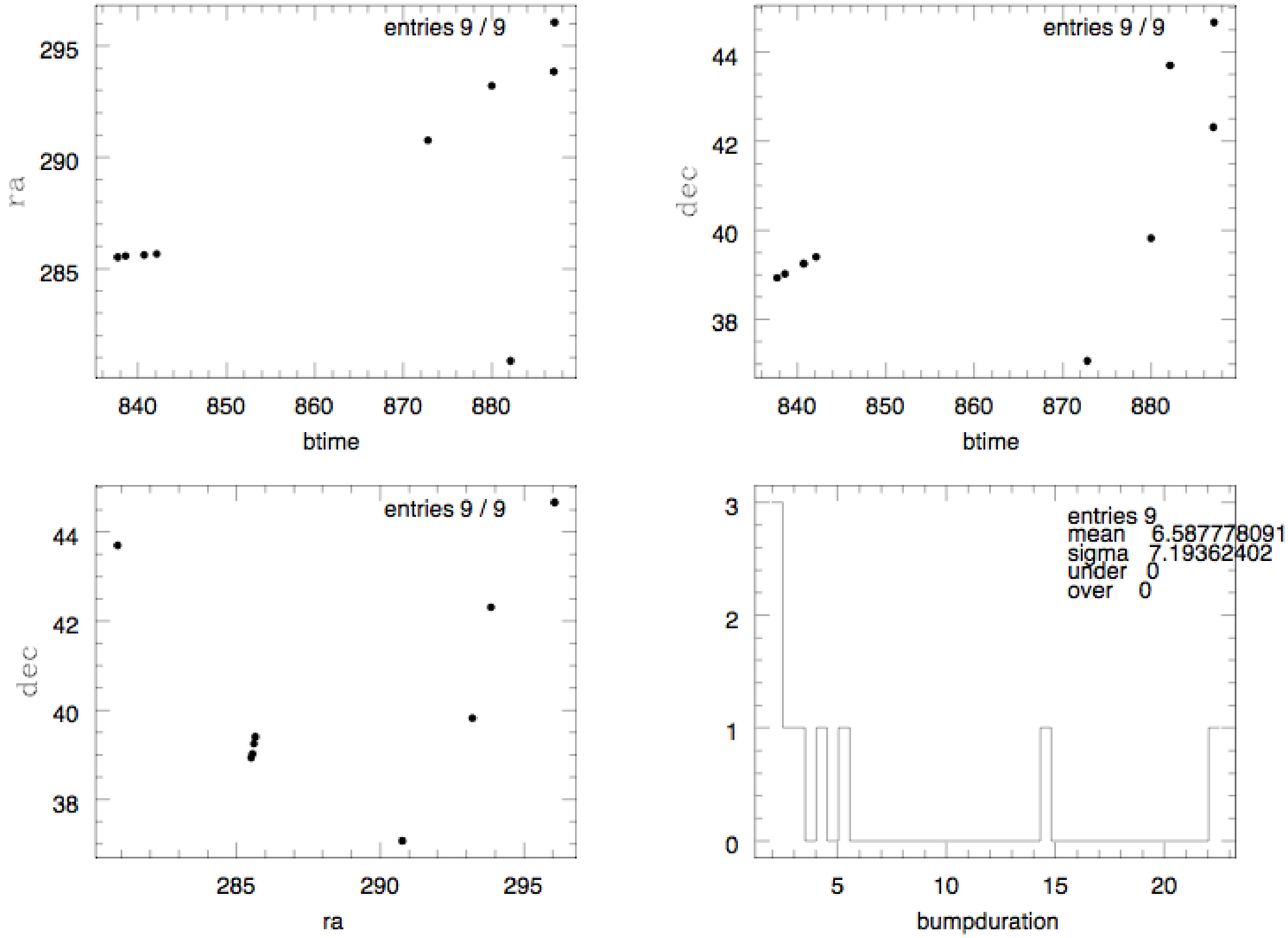
Latest Quarter



Latest Quarter



More Comets…?



entries 9 / 9
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290
285
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42
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870
880
btime
entries 9 / 9
44
42
40
38
dec
285
290
295
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entries 9
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sigma 7.19362402
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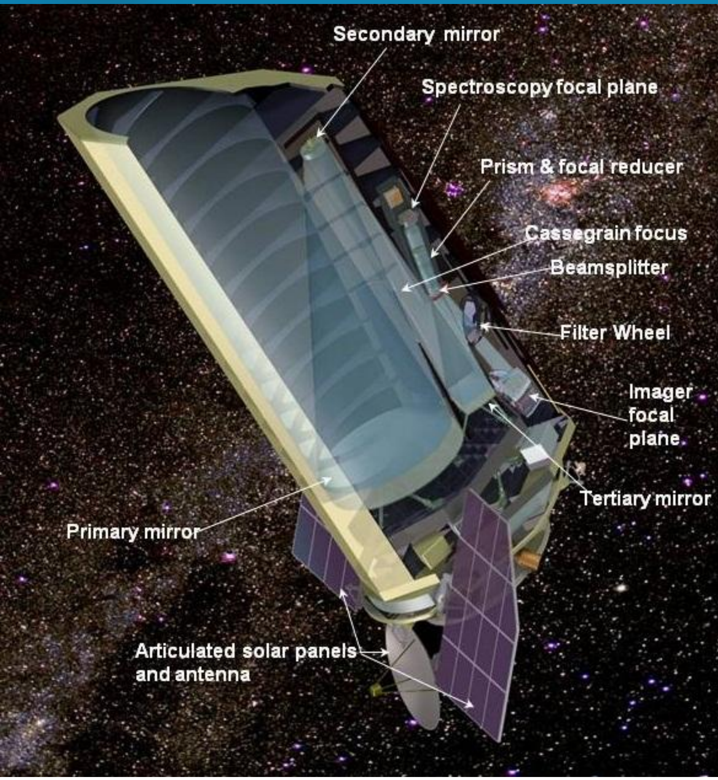

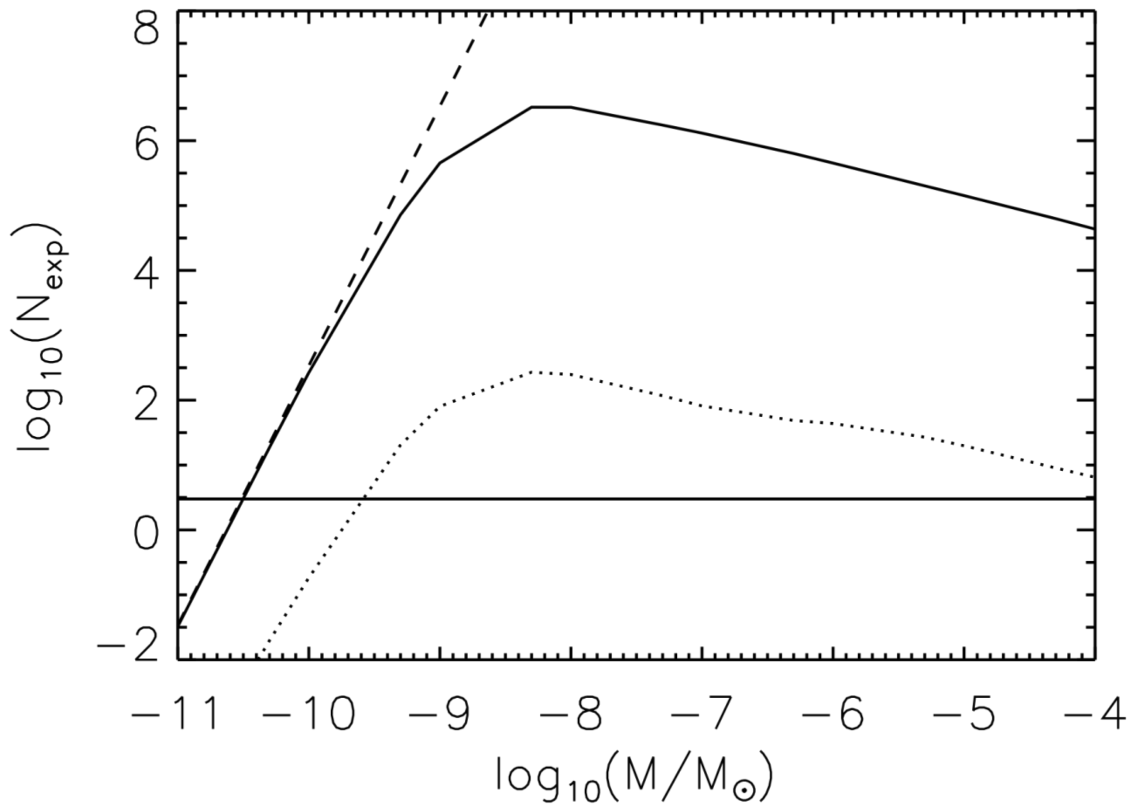

- Designed to search for Dark Energy and extrasolar planets
- Preliminary specifications: 2 x 10^8 stars monitored towards the galactic bulge with a cadence of 15 min and a 1 % photometry precision (Bennett et al. 2010)

A. M. Cieplak and K. Griest. ApJ 2013 accepted.

Summary

- A new formalism for detecting PBH's was developed
- PBH's may be detectable using the Kepler satellite
- Could close 40% of the remaining PBH DM window
- Possible new discoveries such as comets and stellar flares
- Developed approximation for future source selection
- Preliminary constraints coming soon!

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